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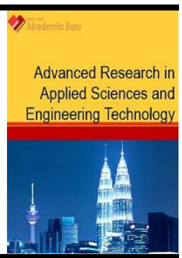


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# Aluminium Alloys in Space Applications: A Short Report

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**ABSTRACT**

Because of the unique combination of light weight, high strength, and ease of fabrication, aluminum alloys have the mainstay of the aerospace industry. This report provides a brief overview of the types and series of aluminum alloys "AA" used for space industries and aerospace applications such as spacecraft surface structures and both of aircraft construction and satellite subsystems. The alloy compositions, manufacturing processes, and treatment classify the alloy properties and characteristics. According to these characteristics alloy compositions, the report outlines how to identify the suitable and optimum one to meet specific application needs and mission requirements. Also, the report clarifies how these alloys can be improved by a suitable tailoring of the composition through the addition of some of the alloying elements, which considerably are useful to refine the microstructure, thus improving the mechanical properties. Different types of aluminum alloys such as the series AA 2XXX, AA 5XXX, AA 6XXX, and AA7XXX are outlined. The discussion is performed to give view point on the alloy series with the emphasis on the improved of the alloy type AA6061, as example, with the heat treatment T6 "AA6061-T6" that is significantly more suitable alloy for spacecraft and satellite' surface structures.



## 1. An Overview

In general, materials properties can be tailored to the anticipated component application by modification of their chemistries and by manipulation of the processing. From Mother Nature, materials scientists have adopted a third approach, the homogeneous, local or directional reinforcement of a component in order to improve properties like stiffness, strength, or toughness. One of these materials is the aluminum. This metal is frequently used in space as it is light in weight. On its own, aluminum is not incredibly strong but when combined into alloys with other metals into it becomes much stronger [1-3]. Aluminum alloys are often strong and lightweight enough to be functional in space structures and satellites. Aluminum and different groups of aluminum alloys (AA6061, AA2024 and AA7075) are important and widely used, which in particular satisfy the

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requirements of space applications with good results. As an example, after thermal cycling on aluminum alloys see that in groups 2XXX and 7XXX, some of these alloys have been observed. On the other hand, aluminum and its alloys are used for the shutters on the windows of the International Space Station in order to protect the windows from impacts [2-3].

## 2. Aluminium alloys: classifications and groups

The aluminum alloys used in space applications are shown in table 1. Chemical compositions of aerospace aluminum alloys are given in this table [2-3].

**Table 1**
Compassions of the aluminum alloys

| Alloy | Cu | Mg | Zn | Mn | Si | Fe | Cr | Ti | Zr |
|---|---|---|---|---|---|---|---|---|---|
| AA2014 | 3.9-5.0 | 0.2-0.8 | $0.25_{max}$ | 0.4-1.2 | 0.5-1.2 | $0.7_{max}$ | $0.10_{max}$ | $0.15_{max}$ | - |
| AA2017 | 3.5-4.5 | 0.4-0.8 | $0.25_{max}$ | 0.4-1.0 | 0.2-0.8 | $0.7_{max}$ | $0.10_{max}$ | $0.15_{max}$ | - |
| AA2024 | 3.8-4.9 | 1.2-1.8 | $0.25_{max}$ | 0.3-0.9 | 0.50 | 0.50 | 0.10 | 0.15 | - |
| AA2219 | 5.8-6.8 | $0.02_{max}$ | $0.25_{max}$ | 0.2-0.4 | $0.20_{max}$ | $0.3_{max}$ | - | 0.02-0.10 | 0.1-0.25 |
| AA5083 | $0.10_{max}$ | 4.0-4.9 | $0.25_{max}$ | 0.4-1.0 | $0.40_{max}$ | $0.4_{max}$ | 0.05-0.25 | $0.15_{max}$ | - |
| AA6061 | 0.15-0.4 | 0.8-1.2 | $0.25_{max}$ | $0.15_{max}$ | 0.4-0.8 | $0.7_{max}$ | 0.04-0.35 | $0.15_{max}$ | - |
| AA7050 | 2.0-2.6 | 1.9-2.6 | 5.7-6.7 | $0.1_{max}$ | $0.12_{max}$ | $0.15_{max}$ | $0.04_{max}$ | $0.10_{max}$ | 0.08-0.15 |
| AA7075 | 1.2-2.0 | 2.1-2.9 | 5.1-6.1 | $0.3_{max}$ | $0.4_{max}$ | $0.5_{max}$ | - | $0.10_{max}$ | |
| AA7150 | 1.9-2.5 | 2.0-2.7 | 5.9-6.9 | 0.10 | 0.12 | 0.15 | 0.04 | 0.08-0.15 | 0.06 |
| AA7178 | 1.6-2.4 | 2.4-3.1 | 6.3-7.3 | 0.30 | 0.4 | 0.5 | 0.18-0.28 | 0.20 | - |
| AA7475 | 1.2-1.9 | 1.9-2.6 | 5.2-6.2 | $0.06_{max}$ | $0.10_{max}$ | $0.12_{max}$ | 0.18-0.25 | $0.06_{max}$ | - |

Generally, several of the aluminum alloy groups in accordance with the Aluminum Association System are listed in table 2 [3-4].

**Table 2**
Aluminium alloy groups

| Alloy Group | Designation |
|---|---|
| Al-Cu | AA2219 |
| Al-Cu-Mg-Si | AA2009, AA2014, AA2048, AA2124 |
| Al-Si-Mg | A359 |
| Al-Mg | A356, AA5083 |
| Al-Mg-Si-Cu | AA6061, AA6082, AA6090 |
| Al-Zn-Mg-Cu | AA7075, AA7090, AA7091 |
| Al-Li-Cu-Mg-Zr | AA8089 |

Some of these alloys with including its element compositions are given as follows;
*AA 6151 (1Mg, 1Fe, 0.8Mn, 0.25Zn, 0.15Ti, rem Al)
*AA 6053 (1.3Mg, 0.5Si, 0.35Cr, rem Al)
*AA 6063 (0.7Mg, 0.4Si, rem Al)

*AA 6061 (1Mg, 0.6Si, 0.25Cu, 0.2Cr, rem Al)

On the other hand, greater weight savings are possible by taking advantage of higher specific stiffnesses and strengths and using more efficient structural concepts. As example, the AA 2219 and 7075 are used in much of the Apollo Lunar Module structure. The alloys AA 2024, 2124 and 2219 are used for parts of the Space Shuttle Orbiter fuselage, the mainstay for tankage, wings and vertical tail because of it is weldable and has good strength and fracture toughness. In general, AA 2XXX and 7XXX alloys are used in satellite configuration and aerospace structures. High strength aluminum alloys remain important in airframe structures. There have been important recent advances in aluminum aircraft alloys that can effectively compete with modern composite materials.

## 3. Aluminum Alloy AA6061

### *3.1 Alloy Compositions*

The aluminum alloy AA6061 is one of the most commonly used alloys, particularly by amateur and hobbyist aircraft builders. It is often utilized in the aerospace industry for wings and fuselages. For spacecraft structures and satellite surfaces, AA6061 is the most widely used 6xxx series alloy. The alloy AA6061 has a good strength, light weight and better corrosion properties [3-6]. The standard amount of the alloy compositions (wt%) used in space applications is given in table 3 [7-9].

**Table 3**
Alloy elements of AA6061

| Si % | Fe % | Cu % | Mn % | Mg % | Cr % | Zn % | Ti % | Unspecified other elements | | Al |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | each | total | |
| 0.4-0.8 | 0.7 max | 0.15-0.4 | 0.15 max | 0.8-1.2 | 0.04-0.35 | 0.25 max | 0.15 max | 0.05 | 0.15 | Rem. |

### *3.2 Effects of Alloying elements in the alloy properties*

The concentrations of the alloy elements play an important role in the alloy characteristics. This can be clarified as follows [8];
Titanium: (Ti) is used as a grain refiner of aluminum alloy castings and ingots (for alloy enhancement).
Magnesium (Mg) and manganese (Mn): increases the tensile strength and particularly yield strength after heat treatment.
Silicon Si: is used with magnesium at levels up to 1.5 wt% in the 6XXX series of heat treatable alloys (enhanced of the heat treatment - T6 temper).
Cupper Cu: responds to solution heat treatment and subsequent ageing, with an increase in strength and hardness and a decrease in elongation in T6 temper.
Iron Fe: iron can improve the alloy stability and bearing characteristics, as well as high strength and hardness at elevated temperatures. If the iron concentration is in lower value, then the tensile properties in the heat-treated condition becomes lower unless the silicon content is sufficient to combine with the iron as FeSi. When sufficient silicon is present, the strength properties are unaffected.
Zinc Zn: In the aluminum alloy AA6061, the maximum amount of the element (Zn) is not exceeding on 0.25%. On the negative side, the increasing additions of both zinc and magnesium lead to decrease the overall corrosion resistance of aluminum, such that close control over the microstructure, heat treatment, and composition are often necessary to maintain adequate resistance to stress corrosion

and exfoliation corrosion. Therefore, more zinc concentration leads to the susceptibility to stress-corrosion cracking of the alloys [10]. It must notify that the addition of the element zinc "Zn" with more concentration values can lead to the alloy 7xxx series, which having the highest strength among aluminum alloys [11].

### *3.3 Alloy properties*

The mechanical properties of the alloy AA6061 with different temps and heat treatment are presented in table (4) [7].

**Table 4**
Mechanical properties of AA6061

| Alloy 6061 Mechanical Property Limits for Rod, Bar, Tube, Pipe and Standard Shapes | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Temper | Section or Wall Thickness (inches) | **Tensile strength (ksi)** | | | | Elongation Percent **Min.In 2 inch** | Typical Brinell Hardness **(500 kg load/10mm)** | Typical ultimate Shearing Strength**(ksi)** |
| | | **Ultimate** | | **Yield (0.2% offset)** | | | | |
| | | Min. | Max. | Min. | Max. | | | |
| **Standard Tempers** | | | | | | | | |
| **0** | All | - | 22.0 | - | 16.0 | 16 | 30 | 12 |
| **T1** | Up thru 0.625 | 26.0 | - | 14.0 | - | 16 | - | - |
| **T4, T4511** | All | 26.0 | - | 16.0 | - | 16 | 65 | 24 |
| **T51** | Up thru 0.625 | 35.0 | - | 30.0 | - | 8 | - | - |
| **T6, T6511** | Up thru 0.249 | 38.0 | - | 35.0 | - | 8 | 95 | 30 |
| | 0.250 and over | 38.0 | - | 35.0 | - | 10 | 95 | 30 |

Additional elements (cobalt, chromium, molybdenum) increase the tensile properties in heat treatment [8]. For CubSat, the maximum yield strength of AA6061-T6 is about 276 MPa. For UCI CubSat it is equal about 241 MPa [12-15]. On the other hand, considerably physical properties of the alloy AA6061 are given in Table 5 [16]

**Table 5**
Physical characteristics of the alloy AA6061

| **Physical Properties** | **AA6061–T6** |
|---|---|
| Density g/cm$^3$ (Lbs/In$^3$) | 2.70 (0.100) |
| Modulus GPa (Msi) | 70 (10.0) |
| Poisson's Ratio | 0.33 |
| CTE @ 25C$^0$ ppm/C$^0$ (ppm/F$^0$) | 23.6 (13.1) |
| Thermal Conductivity @ W/mK$^0$ (BTJ/hr Ft F$^0$) | 180 (104) |
| Specific Heat @ 20C$^0$J/Kg K$^0$ (BTJ/lb F$^0$) | 896 (0.214) |
| Electrical Conductivity @ 20C$^0$, % IACS | 43 |
| Damping Capacity 25C$^0$, 500HZ | 1.05x10$^{-2}$ |
| Fracture Toughness $K_{1C}$ $K_{Si}$√in (MPa√m ) | 23 (25) |

Some of these properties used for structure of the STEP CubSat and Compass-1 CubSat are taken the values written in Tables 6-7 and (7) respectively [14-15].

**Table 6**
Surface properties of STEP CubSat structure

| Component | Material | Density [kg/m$^3$] | Thermal conductivity [W/(m.K)] | Specific heat [J/(kg.K)] |
|---|---|---|---|---|
| Structure | AA6061-T6 | 2700 | 171 | 920 |

**Table 7**
Surface properties of Compass-1 CubSat

| **Al-6061 – T6** | |
|---|---|
| **Density [kg/m$^3$]** | 2700 |
| **Conductivity [W/(m.K)]** | 166.9 |
| **Specific heat [J/(kg.K)]** | 980 |
| **Emissivity (thermal)** | 0.08 |
| **Absorptivity (Solar)** | 0.379 |

The exterior structure of this CubSat has aluminum of thickness with 1mm for both the site plate and that in the middle, while it is equal 2mm for the final top and bottom plates.

### *3.4 Improvement of the Alloy Properties*

Improvements of the alloys can be achieved by a suitable tailoring of the composition and a strict control of the impurities. In particular, AA6061 can be reinforced and improved in its characteristics through the addition of some elements given with the following conditions [10];
**Mg:** aluminum alloy AA 6061 is reinforced with the max weight percentage of Magnesium (1.2% wt). This may improve the physical and mechanical properties such as light weight, high strength, good corrosion resistance, malleability, etc.
**Si:** Higher sufficient silicon concentration is present with the low value of the element Fe (0.25).
**Mg +Si:**
Mg + Si -----Not exceed 1.5% (AA6063 - group I)
Mg + Si ------about 1.5% or more, with the addition of the element cupper of concentration (0.3 % Cu), (AA6061 -group II). This can lead to the alloy AA6061 to be with higher strength than group I. and this needs the addition of some elements as manganese, chromium. It must notify that, some aluminum alloys are susceptible to stress corrosion cracking (SCC) such as the groups 2XXX and 7XXX. Very rarely, SCC occurs in aluminum–magnesium–silicon alloys (6XXX) group [8, 17-18].
**Ni:**
Not exceed (0.2%): high purity aluminum but reduces ductility. In AA6061, it added to improve hardness and strength at elevated temperatures and to reduce the coefficient of expansion.

## 4. Discussion and Conclusion

- Aluminum is a relatively low cost, light weight metal that can be heat treated and loaded to relatively high level of stresses, and it is one of the most easily produced of the high performance materials, which results in lower manufacturing and maintenance costs.
- Aluminum alloy series are the common used alloys
- Alloy AA6061 is suitable and preferring for spacecraft surfaces and satellite structures because of the low weight, low cost, easy to anodize, and commonly available for all temper conditions.

- This alloy contains specific elements with various concentrations. The alloy elements Mg, Si, and Cu are considered the major elements used in the alloy compositions and responsible on the increases in hardness and the tensile strength, in particularly yield strength after heat treatment.
- Other elements with lower concentrations should be added to increase the tensile properties in heat treatment.
- The maximum amount of the element (Zn) is not exceeding on 0.25%. More zinc concentration leads to the susceptibility to stress-corrosion cracking of the alloys.
- The alloy group of the series 6xxx (Al-Mg-Si) is not susceptible to stress corrosion cracking as in the series 2xxx and 7xxx.
- The alloy properties can be improved by;

a- Increase the Mg to the maximum value

b- sufficient silicon concentration is present with the low value of the element Fe

c- the elements Mg added to Si becomes equal 1.5% or little more, with the Cu element of 0.3%

d- Nickel Ni, added with the low concentration to the alloy, leads to high purity aluminum but reduces ductility. It can be added to improve hardness and strength at elevated temperatures, and to reduce the coefficient of expansion.

- Accordingly, the scientists are working to position aluminum to compete with composites for new aerospace programs. As example, the materials development approach is integrated with aircraft needs to provide advanced options for airframe design [19]. The current aluminum product performance goals are challenging suppliers to develop and demonstrate aluminum alloys with significant increases in static strength, fracture toughness, fatigue performance, and corrosion behavior. In addition to the technical challenges, the competitive industry environment and the economic environment are creating significant cost pressure that cannot be ignored. Furthermore, A special breed of composites called Fiber Metal Laminates (FML) have gained a lot of popularity regarding aerospace applications. FML can be defined as the reinforcement of aluminum sheets using alternate layers of fiber-reinforced adhesives. This combination gives a synergistic effect on the composite product that incubates attractive properties of the metal and the reinforcement such as corrosion resistance, thermal insulation, damage tolerance, weight reduction, fatigue endurance, specific strength and cost-effectiveness. The development in FMLs by reinforcing aluminum alloys using Carbon fiber and epoxy reinforcements are performed to be used in applications of other composite systems in Satellites, Launch Vehicles and Space Centers or Spaceports [20].
- Aerospace Industry Experts have a positive outlook about the future of aluminum alloys in aerospace, projecting demand for aluminum will double during the next decade. By the year 2025, there will be a global demand of 80 million metric tons, so, the aerospace industry is increasingly looking at recycled alloys to satisfy the high demand. There is also a push for innovation in the materials used, as well as the design structure of aircraft. For instance, newly developed aluminum-lithium alloys could reduce the weight of aircraft and improve their performance. Aluminum-lithium alloys are advanced materials because of their low density, high specific modulus, and excellent fatigue and cryogenic toughness properties.
- As developing countries become more involved in the aerospace industry, and with increased investment, there will be further innovation in aluminum alloys throughout the years to come.

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