Space Materials: Characteristics, Applications, and Environmental Effects

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***Abstract* - In aerospace industry and satellite systems, the selection of the materials is one of the important parts for designing and space components manufacturing. These materials are important for many space industries such as the vehicle and satellite structures/ configuration, space systems, instruments, sensors and communication subsystems, etc. Many principle factors required for these materials to satisfy the needed missions such as light weight, withstanding and resistance and repulse to the ionizing radiation, smart features, self-healing and other multifunctional capabilities, and exceptional thermal stability, etc. The presented paper gives a short review on the classifications and characteristics of the materials used in space missions and technology. Description of the classification of these materials is presented according to the properties and costs. In addition, some of space environmental effects on these materials are elaborated.**

***Index terms*— Space Materials, Materials Classification, Characteristics, Applications, Environmental Effects**

I. INTRODUCTION

To drive the economic growth and the creation of new jobs, space industries are the key sector that is taken into consideration. The global space economies are predicted to reach £400 billion per annum in 2030. Space scientist, space technologists, and spacecraft engineers have got to learn that the space industry is still expanding, and new workforce requires and understanding why certain design systems and rules exist. The race for space exploration commenced from 1957, when Russian Sputnik satellite weighing 83kg bleeped compliments from outer space to earth. Since this remarkable commencement, concerted efforts have gone into this exploration, investigation and studies of different planets in our galaxy, designing and manufacture of materials in space laboratories, and development of geostationary satellites with different functionalities. These were capable to provide a communication, and navigation for between different regions of the Earth [1-3]. In 1965, after about eight years from launch of sputnik, satellite communication was taken on commercial basis. This is further clarified through the launch of Early Bird. This first satellite stayed stationery over earth until ‘applications’ satellites were built with the collection of individually designed components rather than customized and incorporated systems. Frequently, component interfaces failed to be equivalent and were difficult to match, which consequently resulted in limiting of their overall activity and reduction of system performance. These "applications" satellites, and limited of ‘scientific’ satellites, are now integrating regular and uniformed subsystems in attempting to optimize the performance factors including weight, reliability, and development cost. It appears that the spacecraft designers have given significant importance to its weight/ mass. This requirement is typically governed by the capacity of the launch vehicle which carries it from surface and places it in the desired orbit. On the other hand, low weight of satellite leads to the low launching costs. Another key performance factor, which is namely reliability, can also be purchased if the funds are directed preferentially to reliability and testing programs before launch vehicles. Accordingly, the performance parameters represented by reliability, weight, and cost are all interdependent and considered important decision-making factors.

A key objective of the European manufacturers is setting up of the supporting technology program, which improve and enhance the quality of most of the critical subsystems, layout and affect the design of future operational satellites.

These subsystems include [2, 4-6];

- Communication System — that are considered to transfer information and data between satellite and earth, or data transfer between spacecraft and satellites.
- Power Supply — used for providing electrical power to satellite subsystems.
- On-board Propulsion and Thrusters — for orbital changes, de-orbiting, and the maintenance of satellite's position relative to others.
- Environmental Control — to maintain required temperatures, the degrees and levels of radiation, electromagnetic surroundings, etc.
- Structure — holds and maintains satellite configuration not only on the ground and orbit but through its launch phase.

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- Electric Propulsion — to enhance and optimize the mass in good condition and supports payload
- Star Trackers —employed to assure highly precise attitude and orbital control.
- Modular Payload — this includes antenna that can be different depending on the satellite mission
- Batteries — continuously recharged from high performance solar power production system.

Many of scientific organizations such as the NASA, EU, and ESA, have exploited the measurements to evaluate the maturity of the developing of technologies. This advancement could be in material science or components and device design. In case of materials used for the manufacture of the mechanical parts, an innovation may not be appropriate for immediate implementation thus it demands a continued research for maturity. This leads to technology assessment for a possibility of lab development. Advanced material designs necessitate some tests to confirm and validate the newly developed material properties. Newly designed and developed parts may be adequate for use but the manufacturing processes needs verification through tests on “technology samples”— which are considered the stepladders normally used to facilitate the approvals for space [4, 7].

Accordingly, the choice of the space materials is based on the environmental conditions and the exposure time. This can be verified with either the durability in that environment or the appropriate endurance for degradation of these materials to the end of life. They should be acceptably assembled and maintained, with proper agreement with the other surrounding materials and corrosion avoidance [8]. Most of the innovation in space technology and exploration has been made possible by specific breakthroughs in materials and manufacturing processes, enabling the improvement of highly complicated spacecraft systems, rockets, and satellite components. The materials used in the design and manufacturing of spacecraft hardware must be selected according to their engineering properties and functional requirements for specific applications [9-12].

This research reviews the classifications and properties of space materials used for space systems and applications. Such as, structure and components of satellite subsystems, thermal control for on-orbit, shielding for protection of radiation and for space debris impact, optical devices, solar modules and arrays, seals, and coatings with the adhesive materials. Some of space environmental effects on these space materials are also highlighted.

II. CHARACTERISTICS OF SPACE MATERIALS

Beside the challenges related to flight analysis, various other material challenges must also be addressed for design and manufacture of space systems. These challenges comprise weight reserves, re-usability, and operation in space environment. In many areas, the innovations of materials can overcome launch, landing, operation, and environmental issues in space. All materials used in space technology need to possess a number of unique properties to be effective in space and must meet some criteria [13-15]:

Dimension Stability: A material is stable in dimension and shape with changes in temperature.

Light weight: The material with light weight may lead to the less in cost to the mission.

Toughness and Environmental Stability: Most of the components must be strong and tough in the troublesome and cruel space environment. The use of a model parallel with the software and high-end computer facilities can allow the engineers of space materials to estimate the damaging occurred in structural and electronic materials.

Strength and Stiffness: Material can load before breaking and the flexibility is good or otherwise. These two different considerations can be determined according to the required purpose.

Susceptibility of Manufacture: Some of space materials are hazardous to space environment and are more expensive to put together. This needs requirements to hold and arrange these materials.

Effectiveness and Validation of Cost: The cost including the material production and test methods and procedures is an important factor which must be taken into consideration.

Moreover, the following properties of all space materials must be also considered [14-16]:

- The protection and defense
- The assembly and processing
- The information of the vendor
- The similarity
- The physical assets
- The elastic and inelastic properties
- The optical, electrical, and thermal characteristics
- The environmental conditions and properties related to space use, such as corrosion, the atomic oxygen effects, the off gassing and out gassing processes, and the UV radiation.
- The ability to be formed, and easy for welding
- The compatibility with the fluids

Space environment can mainly put all materials under severe stresses. The conditions of space allow only the strongest products to be used for required assignment and be efficient throughout its operational life. Testing of materials for their use in space is essential to assure that devices using them will operate as per requirement in the worst conditions. Without testing, the efforts of putting satellites into orbit are of no use if the devices become unsuccessful in the heat of the atmosphere or in the cooling space. A methodical equipment and material testing are more than a series of steps in the process. It is therefore, considered an imperative point of ensuring aerospace products will work and do well. These tests may include impacts, corrosion, fatigue, compression, thermal, flexure, flammability, composition and thermomechanical analysis.

III. MATERIALS CLASSIFICATION

Materials used in space applications have been classified according to the required purpose and the constituents of spacecraft and aerospace vehicles. Fig 1 shows an example of spacecraft components, in which a variety of materials are used for the instrumentation manufacturing.

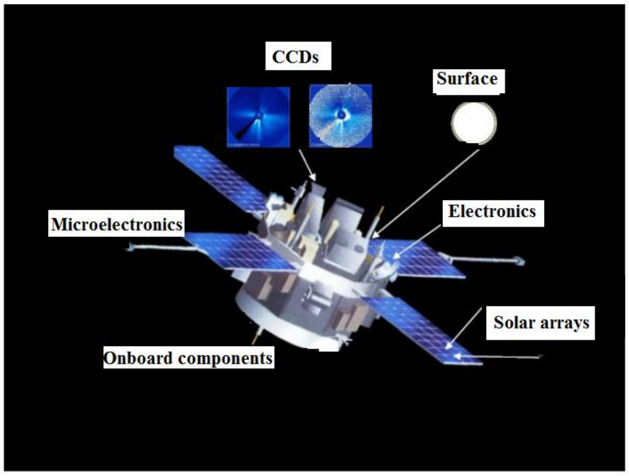

Fig 1: Main of spacecraft 'components

The description for some of these materials can be classified and discussed in subsequent paragraphs.

A. Bulk Materials

These materials comprise basic metals and different alloys. In addition, non-metallic materials as polymers, ceramics, composites and glasses are also classified as bulk materials and placed in this category. Some of these materials are presented here:

Aluminum. The common aerospace material extensively used for space industries, is the aluminum and its alloys due to its high strength/mass ratio. This material is relatively economical as compared to other high-level aerospace materials. Aluminum alloys of the oxide coatings on surfaces have low absorption and high reflection, leading to the occurrence of thermal stability of these alloys under the different thermal conditions of the environment. Moreover, the high-voltage space power systems have prompted designers to take this material into consideration due to its electrical property.

High strength steels In order to use against the higher intensive loads, space engineers considered some of high strength materials as steels, Iron alloys with Carbon, and other elements. Although aluminum has very low density as compared to steel and has a superior strength/weight ratio, but steels possess superior strength. These materials operate with the best quality and possess higher efficiency at different temperature values.

Titanium: Titanium may be frequently chosen in high-strength and high-heat environments.

Super-alloys: Super-alloys are specialty metal alloys, for example, Inconel, nickel-chromium super-alloys. Most of these materials have a considerably great performance in specific applications concerning the environments of high temperature and pressure.

Composites: Composite material is formed from combination of two or more constituent materials. The combination of these constituents results with better physical and chemical properties than the use of individual components. Composites have substantial morphology and play major roles in the presented aerospace studies [17]. Composites have transformed this industry to their multi-directional, tailorable, and multi-functional properties. These properties are important against the tough and severe conditions in outer space [18]. Many composites such as Metal Matrix, Fiber Metal Laminates (FMLs), Ceramic and Polymer Composite Matrix have shown their usefulness in application for satellites, space centers and launch vehicles[19]. The reason behind this significance of use is their dimensional stability, high specific strength, light weight, diverse material combinations and thermal stability. Carbon fiber, a polymer of carbon atoms with high tensile strength has crystalline structure aligned with the long axis of the fiber which makes it special [20].

Usually, Polymer matrix composites have low density with high strength and stiffness. Thus, this property of being light weight declares them as a good candidate for different structural applications. Aluminum alloy composites mostly cover cryogenic and intermediated raised temperature range applications. Titanium alloys are currently used for the applications in the temperature range 500°C –550 °C. Fiber reinforcements are required for use in high wear resistance and stiffness application areas. Fiber reinforcement provides creep resistance and high strength, whereas titanium aluminides provide an additional 200 °C temperature limit capability to structures. Furthermore, super-alloys are proficient for use in high service temperatures up to 1150 °C. Longer uses demand protective coatings to provide safety against oxidation and corrosion. Long-term application requires protective coatings against the corrosion and oxidation processes. Temperature range is further expanded for component operations with the use of thermal barrier coatings. Ceramics although limited usage however, damage tolerance can be added with fiber reinforcement which will also increase application temperature range over 1100 °C [15, 21, 22].

Nanomaterials: Nanomaterials are the advanced and new materials used for the design of various space system components. These advanced materials are highly attractive due to their reduced energy consumption, less weight and volume. However, their survivability in space has not been fully assessed and needs concerted efforts [23-25]. The interaction between nanometer size and ionizing radiation properties need further research for complete understanding which is in hand with different group of researchers [26].

The examinations and analysis of nanomaterials require high technologies with specific diagnoses depending on a range of nanomaterials from 1 to 100 nm. Some of the diagnostic tools needed for the analyses are scanning electron microscopy (SEM), transmission electron microscopy (TEM), and X-ray diffractions (XRD). These materials have significant contributions and applications related to the aviation engineering and space industry. These materials are equally important for use in optical and magnetic applications. As example, it is used in extreme temperature environments with conversion of light into electricity. The applications of nanomaterials are different which depend on the environment, place of use and type of devices. This is established in the use of solar cells for producing clean energy, nano-composites for coatings and exterior surfaces, and sono-chemical de-colorization of dyes by the effect of nano-composite [27].

<u>Graphite</u>*:* Graphite is also used for devices operate in high-temperature areas and suitable for use in the rocket engines. However, instead of the high temperature resistance like Inconel, graphite protects against thermal energy due to its protection against heat. Generally, with the understanding of several advantages and setbacks associated with the different types of aerospace materials, it is easier to interpret and realize the material choice as per requirement and case to case basis. Furthermore, Fig 2Fig 3 illustrate the variation of the material strength with the density and the required cost respectively.

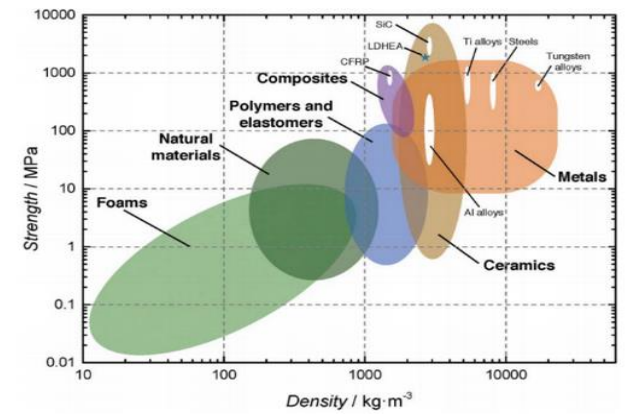

Fig 2: Density and strength of space materials

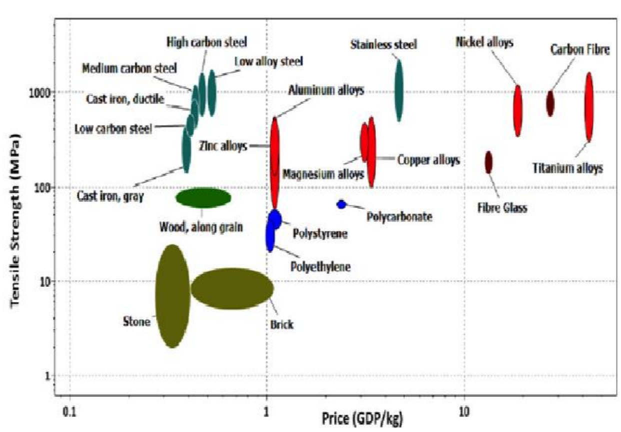

Fig 3: Material strength against cost

The figures reveal a linear trend. This may confirm the materials with the greatest performance are interrelated with higher cost and densities. Therefore, the choice of material for an aerospace project is a balancing act between structures, monetary, and other related constraints.

B. Materials used as protective coatings

These materials are used as filler and protective purposes, and including paints, solder alloys, varnishes, lacquers, lubricants, adhesives, and coatings. Also, the protective materials include the materials concerning sealants and foams, Films, foils, tapes, and inks. These coatings can cause a reduction of out-gassing during mission. Many of composite materials, including metallic, polymers and multi-layer insulator (MLI), organic-based paints, thermal coatings, and thin film shielding, is considered the protective materials. These materials contribute to the vehicle's thermal design and are applied to regulate the surface temperature [28, 29]. Ground-based test could be helpful for determining how well and how long these materials would survive in the inconsiderate space environment [9, 30, 31]. The basic requirements of these materials are principally focused on the following items [32]:

(a) The material must be resistant to the adverse effects of space environment

(b) The materials used for stand and basis, must be light weight, thin and stick strongly

(c) The materials must be free from fault and defect. It must be formed without pores and scratches

(d) It must be non-contaminating

(e) It must not change the fundamental properties of the base and support material

(f) It should have exceptional physical integrity with the base material to resist ground treatment and industrialized loads

(g) It must be stable in the adverse space environment including the particulate and the UV radiations, the impact of orbital micrometeoroids and debris, charging due to plasma interaction, and the vacuum cycling

(h) The requested process must not damage the base material

(i) The cost-effectiveness must be taken into account, and it must be easily scalable to great dimensions.

A sample of materials used for protection is shown in Fig 4, the material for sample number in the figure is elaborated in TABLE 1. These materials are commonly used for rocket bodies, satellites and spacecraft which use the coating for multiple radiation-heat transfer to tune energy transfer at the surface of spacecraft [33-35].

The protective coatings can not only satisfy the environmental requirements but also it can meet the continual demand by aerospace and defense hardware for enhanced surface performance to work under extreme environmental exposures [36].

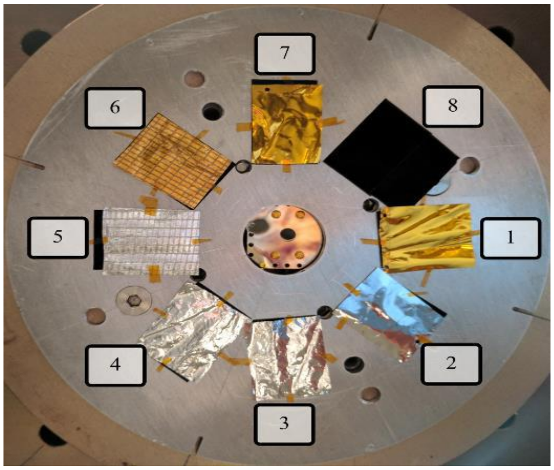

Fig 4: Example of protective materials

TABLE 1
Description of the Labels

Label	Corresponding Material
1	Space-Facing Aluminized Kapton (Kapton Side)
2	Space-Facing Aluminized Kapton (Kapton Side)
3	Aluminized Mylar of Thickness 14 μm
4	Aluminized Mylar of Thickness 17 μm
5	Aluminized Kapton towards Spacecraft facing (Aluminum Side)
6	Aluminized Kapton towards Spacecraft facing (Kapton Side)
7	Space-Facing Aluminized Kapton (Kapton Side)
8	Acktar – Light – Absorbent Foil

IV. SPACE ENVIRONMENT EFFECTS ON MATERIALS

In case of space missions, the used materials are exposed to hostile and severe/difficult environments during operations. The major environmental factors impact the properties of the materials are as under [9, 11, 37, 38]:

Atomic oxygen : it can damage exposed surfaces.

Out-gassing : In the outer space, material releases trapped gas particles when the atmospheric pressure drops to near zero.

Cold welding : In the outer space, a condition that can cause metal parts to fuse together.

Heat transfer : In the outer space, spacecraft can safe its structure from excessive heat only through radiation.

Micrometeoroids : Small particles and space junk can damage spacecraft during a high-speed impact.

Radiation : Primarily the Sun radiation can cause excessive heating on the exposed surfaces. This can damage the electronic components and may result in disruption in communication. It can even end up with charged particles and plasma. The continuous charging and discharging can result in surface degradation, contamination, and sputtered particulates.

These environmental effects can lead to either performance degradation and or failure of many materials such as polymers, composites, paints that are used for power generation and spacecraft ‘surface structure. The materials used in sensitive optical system and spacecraft surfaces when endure space environmental effects induce optical property degradation. Changes in optical property degradation must be characterized during hardware design and often re-evaluated during the operation of long-duration space systems. In a previous paper, Abd el-Aziz et al studied the space plasma environment and its effects on many samples of the materials used for satellite surface structures as well as the plasma effects on the efficiency and performance of the solar cells. The authors have confirmed the material degradation and deformation under the effects of plasma exposure. Less performance and efficiency of the solar cells is also found out due to plasma exposure [39-41].

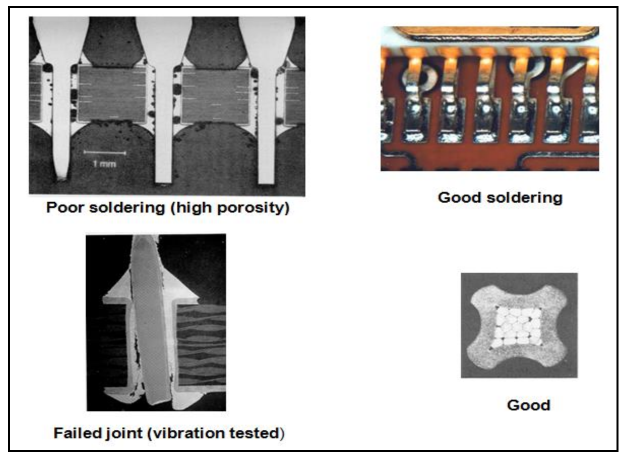

Fig 5: Example of material process

V. FORMATION PROCESSES AND TREATMENT

Specific material requirements need to be satisfied for space manufacturing applications. Fig 5 shows samples of some processes and machining materials [1]. The development of these materials undergoes several processes to become suitable for space applications and verification before their use. These processes include:

- Adhesive bonding
- Composite manufacturing
- Encapsulating
- Painting and coating
- Cleaning (for electronic assemblies)
- Welding and brazing (simple welders)
- Crimping/gathering and wire wrapping
- Soldering processes
- Surface treatments (as per aerospace standards)
- Plating (for electronic assemblies)
- Machining
- Metal forming
- Marking
- Non-destructive check
- Miscellaneous processes such as: casting;

mechanical joining; fabrication; etc.

In addition to all above process the heat treatment process having significant contribution to performance must be taken into consideration. This process, namely the temper process, checks the degree of hardness of the used material. In case of aluminum alloys, the heat treatment is performed at temperatures up to 990 ˚F [42, 43]. This treatment is applied on metals and alloy materials. On the other hand, the annealing process is the next important process considered and applied on the materials to enhance their required material properties. This process is utilized to remove the internal stresses to rescue the material from unwanted changes in toughness and hardness properties. Most of space materials and components must be examined through the thermal cycling vacuum test. These processes should be applied under specific conditions and performed to determine the ability of the material and components concerning aerospace industries to withstand variations in ambient temperature under vacuum and other related space environment.

VI. CONCLUSION

Materials used in the aerospace industry have been reviewed. Classification and characteristics required for space industry and aerospace engineering have been elaborated. Different properties essentially required for space applications and impact of environmental conditions on these materials is outlined. This review could be helpful for the scientists and space engineers for understanding the material properties that are essentially required in space applications. It also assists the readers related to space industry to appreciate the importance of different factors considered during selection of the suitable and optimum material to meet the required purpose for specific space system and subsystems. Material engineers can determine the equipment and tools to enhance the performance of space systems and devices to prevent failure and ensure their working with high-quality during design life. Also, they can develop the processes for verification of material properties imperative for long-duration space missions. Finally, for any space mission and project, the choice and identification of materials is a balancing process or calculated compromise between structural configurations the monetary values, and other related constraints.

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