Application of New Materials in Aerospace Thermal Management

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Abstract. This paper summarizes the mission, scheme and main technology of spacecraft thermal management. The development requirements of new thermal control technologies, especially new thermal control materials, for future spacecraft are analysed. The research progress of new high thermal conductivity materials, new interface filler materials and intelligent thermal control coatings at home and abroad and their applications in the thermal control field of spacecraft are reviewed.

Keywords: Aerospace thermal control; high thermal conductivity material; Interface filling material; Intelligent thermal control coating.

1. Introduction

The same as the conventional electronic and electrical equipment on the ground, any equipment, instrument, circuit and device on the spacecraft must work at a certain temperature level to play its function, performance and maintain its life. As the common electronic equipment is required to work at -15 ℃~50 ℃, the battery is required to work at -5 ℃~30 ℃, and the CCD and other precision photoelectric devices must work at temperature fluctuation less than ±2 ℃. The thermal control of spacecraft is independently set as a subsystem, which constitutes the spacecraft together with attitude and orbit control, structure and mechanism, data transmission and control, measurement and control, and payload system. The main task of spacecraft thermal control is to control the structures/mechanisms, equipment and instruments, and circuit components on the spacecraft within a reasonable temperature range[1],[2].

The temperature level of spacecraft is mainly affected by internal and external factors. Internal factors include waste heat generated by power equipment, thermophysical properties and temperature sensitivity of internal structures/devices; External factors mainly include vacuum, 4K cold space, stellar/planetary radiation heat flow, microgravity, and atmosphere. Therefore, the overall scheme of spacecraft thermal control is as follows: 1) For internal factors, technologies such as collection, transmission, storage and dispersion are mainly adopted to reasonably allocate or disperse the waste heat generated by power equipment to 4K cold space; 2) For external factors: take thermal isolation and thermal protection measures to weaken the radiation, aerodynamics, convection and other heat transfer effects of 4k cold space, radiant heat flow, atmosphere, etc. on the surface of spacecraft. That is, the main thermal control technologies of spacecraft include heat acquisition technology, heat transfer (heat conduction) technology, heat storage technology, thermal insulation/thermal protection technology, heat dissipation technology, etc.

In the future, spacecraft will undergo significant changes in scale, mission and other directions, and spacecraft thermal control technology should also be developed adaptively. The power of space stations and communication satellites reaches tens to hundreds of kilowatts, which is one order of magnitude higher than the current level. More efficient heat acquisition, emission and transmission technologies are required; Micro/nanosatellites are small in size and scarce in resources. Due to the complex and unknown external heat flow, the deep space exploration mission requires lightweight thermal insulation materials and intelligent heat radiation dispersion technology.

The function and performance of most thermal control technologies are based on the characteristics of their own materials. The development of new materials will have an important impact on the improvement, even subversion, of the performance of existing thermal control technologies. The research progress of new high thermal conductivity materials, new interface filler materials and new thermal radiation materials and their applications in the thermal control field of spacecraft are summarized in the following.

2. New High Thermal Conductivity Materials

Thermal conductive materials are mainly used for heat diffusion and transmission of power devices on spacecraft, as well as temperature equalization of structures. For example, aluminum alloy materials are usually used as heat diffusion plates for power devices in electronic equipment; The radiation radiator and the front mirror tube of the space remote sensor with high temperature sensitivity are mostly made of aluminum alloy or carbon fiber; The expander of the cryogenic refrigerator is made of copper; Circuit components with flexible heat dissipation requirements such as camera focal plane will use flexible heat strap made of copper strap for heat transfer.

In the process of the development of spacecraft electronic equipment toward miniaturization, lightweight and compactness, traditional materials such as copper and aluminum, due to their limited thermal conductivity, high density and high thermal expansion coefficient, have gradually been unable to meet the heat dissipation and temperature equalization needs of electronic equipment and other structural parts. Therefore, many scholars at home and abroad have studied new multi-functional thermal conductive materials, including diamond graphite and graphene and their various derived composites.

2.1 Metal Matrix Composite

With the advantages of high thermal conductivity and adjustable thermal expansion coefficient, metal matrix composites have broad application prospects in many fields such as electronics and thermal management [3]. The metal matrix composites with high thermal conductivity mainly use copper and aluminum as the base materials, and the commonly used reinforcement materials are silicon carbide, graphite and diamond [4] [5].

Copper/diamond composites are considered to be one of the most ideal electrical packaging materials, but at present, many copper/diamond composites are difficult to obtain good performance, such as high heat transfer coefficient. The main reasons are as follows: (1) The larger wetting angle between liquid copper and diamond leads to the poor compactness of copper/diamond; (2) The density difference between copper and diamond is large, which makes it difficult to achieve uniform distribution of diamond and copper in the composite; (3) There is almost no chemical reaction and solid solution between copper and diamond, which leads to poor adhesion between copper and diamond sections.

As a result of the above reasons, most of the copper diamond composites studied in the early stage are simple mechanical bonding, and the interface pores are large, which is easy to have defects, which leads to the thermal conductivity and mechanical properties of many copper diamond composites can’t meet the requirements, even lower than copper itself. At present, the solutions mainly include: (1) exploration of new processing methods, mainly including high-temperature and high-pressure method, casting, electrodeposition, electroplating, sintering and other technologies; (2) Add interface improvement materials, that is, add transition layer metals between copper and diamond, wherein the transition layer metals mainly include titanium (Ti), zirconium (Zr), molybdenum (Mo), etc.

Ruxia Liu et al. [6] made copper/diamond composites by adding Mo2C transition layers of different thicknesses between copper and diamond using ion beam activated sintering technology. When the content of Mo2C is 3.25%, its thermal conductivity is 351W/m·K. Although its thermal conductivity is not as good as that of copper itself, its thermal expansion coefficient is only

$9.27\times10^{-6}K^{-1}$ through diamond reinforcement, has certain application prospects in the field of thermoelectric packaging.

Luhua Wang et al. [7] made copper-based zirconium alloy with diamond particles as reinforcement by air pressure infiltration method, and observed the interface structure of Cu Zr/diamond composite material by scanning electron microscope. At the same time, it was pointed out that the thermal conductivity of the composite decreased with the increase of zirconium proportion. The optimal proportion of zirconium was 0.5%, and its thermal conductivity was 930W/m·K. Yanfeng Pan et al. [8] [9] put forward a new method to improve the interface between diamond and copper by using zirconium carbide to produce diamond/copper composite, with a thermal conductivity as high as 720W/m·K.

Hai Jun Cho et al. [10] obtained a copper-based diamond composite by electrodeposition. When the diamond content is 68.2%, the maximum thermal conductivity measured is 454W/m·K; Then TiC was used as an improved material, and TiC coating was added to diamond particles. When the diamond content was 34.7%, the thermal conductivity could reach 557W/m·K.

L. A. Elshina et al. [11] made Al-Al2O3-graphene composite by adding 10% aluminum oxide and 0.2% graphene to pure aluminum. Through measurement, its thermal conductivity increased to 272.1W/m·K, which was significantly higher than that of pure aluminum (202W/m·K), and its hardness and strength increased by twice, as well as its corrosion resistance.

Rajendran. M et al. [12] added different proportions of SiC and coal ash into aluminum alloy to make aluminum matrix composite by stirring casting, and measured its thermal conductivity range from 406W/m·K to 443W/m·K.

Essam. A. M. et al. [13] used A359 aluminum alloy as the base material and AlN and SiC as the reinforcement materials to make aluminum matrix composites. The effects of different proportions of AlN and SiC on the thermal conductivity and wear resistance of A359 aluminum alloy reinforced materials were studied. The results show that the thermal conductivity of A359/AlN composite is better than A359/SiC and A359, and it also shows better abrasion resistance.

2.2 Diamond and its Composites

Diamond is the best thermal conductive material among the existing natural materials, with the highest thermal conductivity of 2000W/m·K, almost four times that of copper. The poor performance of early artificial diamond is mainly due to the large defects in the diamond interface due to the limitation of production technology, and the high price of natural diamond, which makes the research and development of diamond materials slow. In recent years, with the improvement of the quality of synthetic diamond, more and more scholars began to conduct in-depth research and application attempts on the high thermal conductivity of diamond. In addition to being used as the reinforcement of metal matrix composites, diamond has also been explored by scholars in other countries.

Yixuan Xue et al. [14] studied the diamond nanowire tow and found that its thermal conductivity has strong anisotropy. The thermal conductivity in the longitudinal and latitudinal directions is about 300 times different. The study also found that when different tensile/compressive deformation is applied along the longitudinal direction, the thermal conductivity will change significantly. The author thinks that it has a very good application prospect in supercapacitors.

J. M. Molina et al. [15], in order to solve the problem of poor thermal conductivity of materials encountered in the field of electrical conversion, prepared a diamond iron composite by adding Ag and Ag-3wt% Si using the air pressure infiltration method. The material has a thermal conductivity of more than 200W/m·K, while its relative permeability is more than 0.3.

Long Zhang et al. [16] made a 3D foam diamond to enhance the heat transfer capability of energy storage phase change materials, and paraffin was used as phase change material, that is, paraffin was filled in the pores of foam diamond. They compared the heat transfer performance of foam diamond/paraffin, diamond powder/paraffin, foam copper/paraffin, and pure paraffin, and their heat transfer coefficients were 6.70W/m·K, 0.45W/m·K, 2.56W/m·K, 0.25W/m·K, respectively, even though the volume ratio of foam diamond is only 1.3%, its heat transfer performance is still 162% higher than that of foam copper/paraffin, and 2580% higher than that of pure paraffin.

3. Intelligent Thermal Control Coating

Due to the characteristics of ultrahigh vacuum in space, spacecraft and outer space exchange heat mainly through radiation. The outer surface of the spacecraft will radiate and dissipate heat to 4K deep cold space, and at the same time, it will absorb the radiation heat flow from the sun, the earth and other celestial bodies. The thermal control coating shall be mainly applied to the outer surface of the spacecraft, and the heat flow exchange of the spacecraft in outer space shall be adjusted by designing the absolute value and ratio of solar absorptance and infrared emissivity. For example, high infrared emissivity and low solar absorptance are used for radiating radiator to achieve heat dissipation efficiency; For multilayer thermal insulation components used for thermal insulation, the outermost wall surface is usually coated with low infrared emissivity and solar absorption. For different emissivity and absorptivity, conventional thermal control coatings mainly include: polished metal surface (low emission), sandblasted metal surface (medium emission, medium absorption), anodized coating (adjustment of absorption ratio), electroplating coating (adjustment of absorption ratio), organic paint (high emission), inorganic paint (high emission), secondary surface mirror, etc. (high emission, low absorption).

With the increasingly stringent requirements for energy and quality of spacecraft and the development of deep space exploration technology, intelligent thermal control coatings that can adaptively adjust the absorption/radiation ratio with temperature change are increasingly favored by designers. Intelligent thermal control coatings mainly include electrochromic coatings and thermochromic coatings.

3.1 Electrochromic Material

Electrochromic refers to the reversible color change phenomenon in appearance due to the change of reflection and transmission of light caused by the oxidation or reduction of materials themselves under the effect of external electric field. Using the characteristics that electrochromic materials can change the optical properties according to the size of external voltage, engineers have developed electrochromic devices with light weight, small volume and low energy consumption. Through the electrochromic device, the absorption and emissivity of the spacecraft surface can be independently changed according to the specific thermal control needs, so as to realize the intelligent thermal control of the spacecraft.

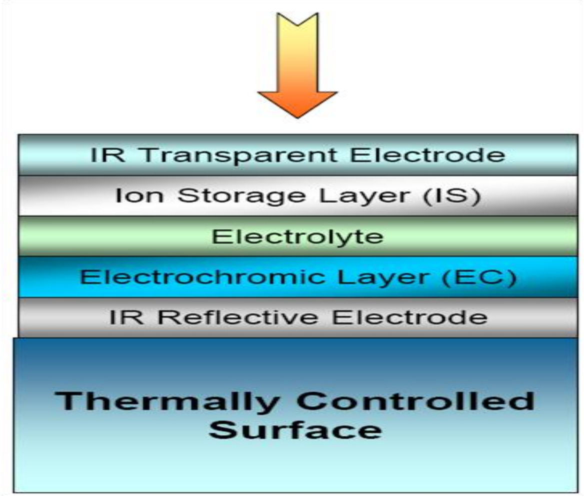

Figure 1. Structure of electrochromic device.

At present, the main development directions of the Department of Defense (DOD) and the National Space Administration (NASA) in the intelligent thermal control coating technology that can be used for aerospace applications are electrochromic variable absorption emission thermal control coating technology, electrostatic switch variable absorption emission thermal control device based on electrophoresis technology, and MEMS louver variable emissivity thermal control module. Among them, the electrochromic intelligent coating has an important position in the development of aerospace thermal control technology due to its advantages such as large absorption emission variable range, stable performance, low power consumption, light weight, simple structure, and no mechanical components. NASA reported that the application of intelligent thermal control coating technology can save about 90% of energy consumption and 75% of weight, which is especially suitable for small satellites with small power consumption and mass volume.

Hale et al. [17] prepared WO3\NiO\Ta2O5\Au\ITO thin film devices by magnetron sputtering. WO3 is the device colour changing material, which is mainly used to adjust the emittance of the device. The adjustment range of the emittance of the device measured by experiments is 0.057 to 0.595. In 2000, Franke [18] et al. prepared emissivity modulation devices (2-40 μm) in the infrared region from the mid infrared region to the far infrared region by magnetron sputtering. The top electrode is aluminium grid electrode, the light transmittance of this electrical level can reach 90%, the colour change layer material is polycrystalline WO3, the ionic conductor is Ta2O5, and the ion storage layer is amorphous WO3, with the emissivity change rate of 20%.

Scientists from Ashwin Ushas Company invented a thin film electrochromic coating with a thickness of less than 0.5mm, which can protect the aircraft from the threat of extreme cold or hot conditions in outer space, and can withstand the impact of micrometeoroids flying at thousands of miles per hour. Under vacuum conditions, the film can continuously circulate between minus 58 °F and 212 °F (minus 50 °C and 100 °C) for three consecutive months, and the temperature of the wrapped articles is kept between 122 °F and 176 °F (50 °C to 80 °C); The electrochromic intelligent thermal control coating prepared by the company has a large range of emissivity adjustment in the wide frequency range of mid infrared and far infrared, wherein the infrared emissivity is 0.18～0.68 or 0.39～0.89, and the emissivity changes to 0.5 [19]-[21]. The emissivity change rate of the electrochromic device developed by Ashwin Ushas Corporation can reach 0.53, and the thermal emission performance in the high temperature region can be the same as that of the surface mirrors (OSR) and secondary surface mirrors (SSMs); In the eclipse area, variable emitter devices have low emissivity. Compared with traditional thermal control methods, electrochromic thermal control coatings can reduce load power consumption by 70% [22].

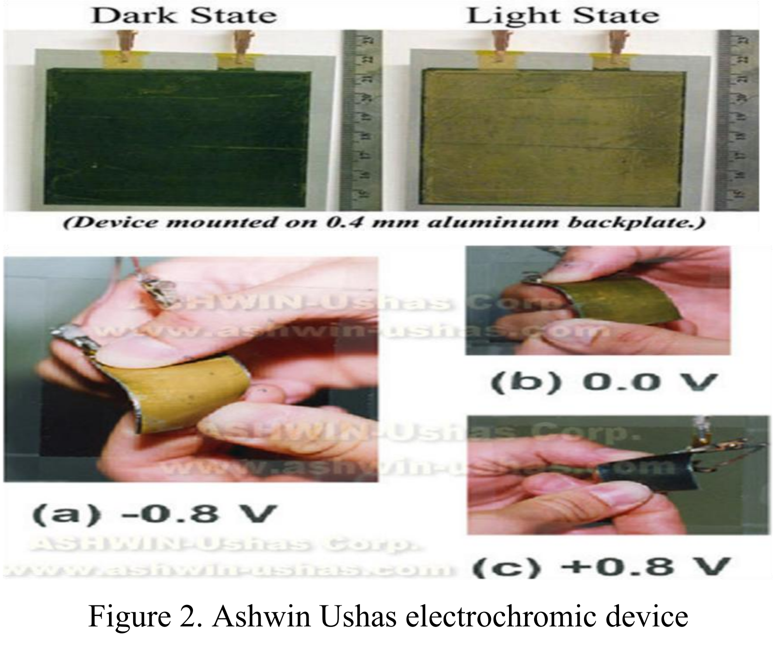

Figure 2. Ashwin Ushas electrochromic device

Demiryont, H. et al. [23] reported a solid thin film infrared electrochromic device, whose variable emission performance can be used for thermal control of spacecraft antenna. The reflectivity of the element is about 60% in the range of 4.2-27 μm; In the fading state, it shows more than 90% solar reflection. At 1.6V bias, the device switches to absorption mode (colored state), and its emissivity rises to 0.98; When 0.6V reverse voltage is applied, the element returns to reflection mode. Therefore, the device is expected to be used as an intelligent variable emission component for spacecraft or satellite surface to adjust the thermal emissivity of spacecraft surface.

Chandrasekhar, P. et al. [24] have developed an infrared electrochromic device based on a conductive polymer. The device is less than 0.5mm thick and light. It can change color at room temperature for less than 0.5 seconds. It can still be used normally after more than 104 cycles of color change. The device has low power consumption. The biggest advantage is that it can still have high stability in a space hostile environment. The device has been verified in flight on spacecraft, which proves that the technology has great application value in micro satellites. Yanchun He et al. [25] designed a solid-state electrochromic film for spacecraft thermal control system applications. The device structure is ITO/WO3/Ta2O5/NiO/glass substrate. The theoretical calculation shows that the solar absorption ratio of the device is 0.549 after being electrochromic, 0.213 when it is not discolored, and the solar absorption ratio is increased by 0.381; The change of infrared emissivity of the material is 0.49. Teissier et al. [26] carried out the research on the application of polyethylene and polythiophene copolymer (PEO/PEDOT) as satellite thermal control materials. The maximum emissivity change is 0.31, the color change time is less than 3 seconds, and the energy consumption is less.

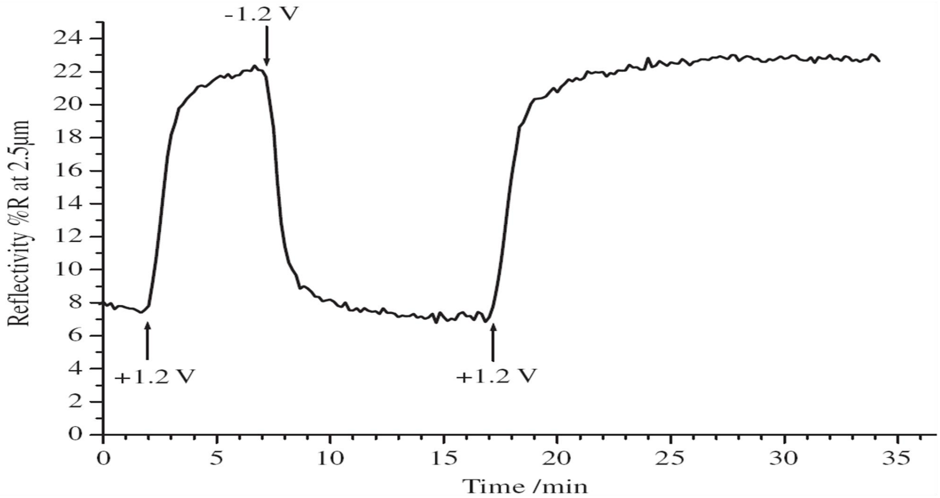

Figure 3. Emissivity changes of PEO/PEDOT electrochromic devices

3.2 Thermochromic Materials

Thermochromic material refers to the property that when the temperature of the material changes, the magnetism of the material changes, resulting in the change of the material's ability to reflect and absorb light. Researchers at home and abroad use this property of thermochromic materials to develop intelligent thermal control components whose emissivity changes with the change of their own temperature. Usually, a perovskite type manganese oxide is used as a thermochromic material, and its emissivity can increase with the increase of temperature. At the beginning, the ceramic chips added with this material were directly bonded to the surface requiring heat dissipation. However, with the development demand of miniaturization and lightweight of spacecraft, the application way of making thermochromic materials into films and coatings has become the focus of researchers.

NEC Company of Japan added thermochromic materials to ceramics and developed a thermochromic patch type thermal control device. Through experimental testing, it was found that when the device temperature gradually increased from 173K to 373K, the surface emissivity would also increase, and the state of the material would change. When the temperature was lower than the phase change point, the emissivity was lower in the metallic state, and when the temperature was higher than the phase change point, the emissivity was higher in the insulating state. The adjustment range of the emissivity of the measured material surface is 0.37 to 0.41 [27].

Canadian researchers also conducted in-depth research on thermochromic materials. They prepared La1-xAxMnO3 (X=0.175,0.3) films [28],[29] with a thickness of 150μm. Through the test of the emissivity of the film, it is found that different materials of the substrate will affect the structure of the film crystal, thus affecting the emissivity of the film. The emissivity change of the film on the metal substrate is more obvious than that of the substrate of other materials in the same temperature range. The emissivity of the films prepared by magnetron sputtering varies in the range of 0.25.

4. Thermal Interface Material

Contact thermal resistance significantly affects the heat dissipation efficiency of power equipment/devices. When the heat flow density is 1W/cm2, the temperature difference caused by interface thermal resistance is as high as 50 ℃. The interface filling material acts on the installation interface between power equipment/devices, heat transfer devices and heat sinks, filling the micro gaps or micro pores generated by the roughness of the two contact interfaces, thereby increasing the effective contact area of the two interfaces and effectively reducing the contact thermal resistance. The thermal conductive fillers used in the field of aerospace thermal control include thermal conductive silicone grease, thermal conductive silicone rubber, thermal conductive insulating pads, etc. Generally, when two smooth metal surfaces contact, the thermal conductive filler can increase the contact heat transfer coefficient by more than three times.

However, with the enhancement of spacecraft functional performance and integration, the heat flow density of laser, radar, microwave and other space loads has reached 10 W/cm2 to 500 W/cm2, and the performance of existing thermal conductive fillers is far from meeting the requirements. New interface materials such as carbon nanotubes and graphene doped with high thermal conductivity are expected to solve the above problems.

4.1 Carbon Nanotube Array Thermal Interface Materials

In 1985, Kroto, Smalley and Curl discovered zero dimensional fullerenes when evaporating graphite electrodes with lasers. Since then, researchers have begun to study carbon nanostructures [30]. In 1991, Professor Iijima, a Japanese electron microscopist, observed and confirmed the structure of carbon nanotubes under a high-resolution transmission electron microscope [31]. In 2004, Dr. Geim and Dr. Novoselo of the University of Manchester, UK successfully prepared carbon graphene with two-dimensional structure by mechanical stripping method [32]. One dimensional carbon nanotube can be obtained by rolling a single layer of graphene into a hollow tube. According to the number of graphene layers constituting carbon nanotubes, carbon nanotubes can be divided into single wall carbon nanotubes, double wall carbon nanotubes and multi wall carbon nanotubes.

Berber et al. obtained through simulation calculation that the thermal conductivity of a single carbon nanotube can reach 6600W/m·K. Since then, many researchers have obtained that the maximum thermal conductivity of a single wall carbon nanotube is above 6000 W/m·K [33]-[37] through theoretical simulation, and the thermal conductivity of a single wall carbon nanotube is higher than 3000 W/m·K [38] through experiments. Because carbon nanotubes are nano scale, it is difficult to measure their thermal conductivity accurately by experiments. The size of carbon nanotubes, whether there are impurities, especially the number of structural defects, will greatly affect the thermal conductivity of carbon nanotubes [39] [40]. Chen et al. used molecular dynamics simulation to calculate the influence of a single carbon nanotube with a certain number of defects on its heat transfer performance, and found that its thermal conductivity decreased by 3 times [41].

Due to the high contact thermal resistance between single carbon nanotubes, carbon nanotubes are usually added into thermal interface materials in the form of arrays to improve the thermal conductivity of thermal interface materials. The thermal conductivity of a single carbon nanotube is very high, but the thermal conductivity of the carbon nanotube array is much lower due to the low density and the existence of defects. Wang et al. [42] found that the thermal conductivity of the prepared vertical array of carbon nanotubes dipped in epoxy resin decreased from 17.76 W/m·K to 13.15 W/m·K; The thermal conductivity of the polymer was further reduced to 8.23 W/m·K after the addition of toughening agent. It is found that the measured thermal conductivity of carbon nanotube arrays is only 10 W/m·K, which is quite different from the theoretical value [43]. Akoshima et al. used liquid volatilization to increase the density of carbon nanotube arrays to explore the relationship between density and thermal conductivity of carbon nanotube arrays. The experiment found that the thermal conductivity of carbon nanotube arrays increased by 20 times [44] [45] after the density was increased by 15 times. However, the relationship between the two is not linear. This is because with the increase of its density, the force between carbon nanotubes increases, and the phonon scattering increases, resulting in a decrease in the thermal conductivity of a single carbon nanotube. Therefore, the thermal conductivity will eventually become stable [46].

Figure 4. Carbon nanotube array photos (Left: SEM photo; Right: Suspended carbon nanotube array formed by cutting)

4.2 Graphene Composite Thermal Interface Material

Graphene is a two-dimensional carbon material with carbon atoms arranged in honeycomb. Graphene can be regarded as the basic unit of other carbon materials, and single-walled carbon nanotubes can be obtained by curling it into tubes. Because the covalent bond between adjacent carbon atoms of graphene is very strong, graphene materials have high elastic modulus [47], thus have strong structural stability, creating conditions for its ultra-high thermal conductivity. Balandin et al. [48] first measured the thermal conductivity of single-layer graphene at room temperature by experimental method in 2008, which is 4840-5300W/m·K, much higher than that of common thermal conductivity materials such as diamond and copper. Because of its super high thermal conductivity, graphene as a filler and thermal interface material has become the focus of research.

Epoxy resin is a common matrix material for graphene to meet the requirements of thermal interface materials. Shahil et al. [49] filled graphene into epoxy resin as a filler to prepare composite thermal interface materials. The experimental measurement shows that the thermal conductivity of the composite can reach 5.1W/m·K when the volume fraction of graphene filler is 10% when the single layer and multi-layer graphene are added to the matrix together, which is 23 times higher than that of the epoxy resin matrix. When only multilayer graphene is used, the thermal conductivity of the material increases by 20% when the volume fraction of graphene is 1%. Regev [50] et al. prepared an interface material composed of graphene and epoxy resin, and observed the internal structure of the composite. It was found that when the volume fraction of graphene increased to a certain value, graphene overlapped with each other, leading to sudden changes in the thermal conductivity of the composite. Wang et al. [51] prepared graphene oxide and epoxy resin composites, which were measured by experiments. When the volume fraction of graphene oxide is 5%, the thermal conductivity of epoxy resin is increased by four times.

Although graphene as a thermal conductive filler has made some progress in preparing composite thermal interface materials in recent years, there are still some problems in practical applications. For example, the thermal conductivity of graphene is affected by many factors. Defects and doping will reduce its thermal conductivity. Surface modification can improve the heat transfer ability of graphene and the matrix material, but will reduce its own thermal conductivity. The inability to mass produce high-quality graphene is an important factor that restricts the application of graphene in thermal interface materials. The combination of graphene and other fillers can make up for the deficiency of graphene's own structure, which is the key direction of future research.

5. Conclusion

With the improvement of energy density and integration of spacecraft in the future and the development of complex and unknown space environment, it will also be a development trend to significantly improve the performance of various thermal control technologies. New thermal control materials will also help improve the performance of existing thermal control technologies, or even reform. This paper summarizes the research progress of new high thermal conductivity materials, new interface filler materials and new thermal radiation materials and their applications in the thermal control field of spacecraft, and gives the following suggestions:

(1) Proceeding from reality, the development of high-quality thermal conductive materials for the needs of the aerospace industry cannot be aimed at meeting a single performance index. It is necessary to achieve specialized research on high thermal conductive materials for specific requirements. This requires the consideration of multiple properties and the comprehensive consideration of the requirements of mechanical, electrical, thermal and other disciplines, which is also the general trend of future development.

(2) Although many high-performance materials have been developed at this stage, many materials are still in the laboratory stage. Many materials have low yield, poor performance reliability, strong randomness, and have not yet achieved mass production, which also leads to high cost of materials and is difficult to promote and apply. We should continue to carry out in-depth research. We can take the lead in the aerospace industry, demand drives production, promote military products to civilian products, and promote the development of the entire industry. We should not let the research remain in the laboratory stage.

(3) At the same time, the relevant national departments should increase investment in relevant fields, promote the development of this field to a high, precise and sophisticated level, narrow down or even catch up with the world's advanced level in terms of research depth and breadth, and be forward-looking. The application of high thermal conductivity materials must be accompanied by multidisciplinary development.

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