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Research Progress and Future Trend of Space Materials Science

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Abstract: Space materials science is an interdisciplinary field formed by the integration of materials science and space technology. It originated from the space exploration experiment in the mid-20th century and gradually grew into materials with the rapid development of manned spaceflight.

Science is a relatively complete branch discipline. China is about to usher in its own space station era, thus providing a broader prospect for this new discipline. In this paper, the main research progress in four aspects, including physical and chemical characteristics of space environment, liquid properties and phase transition dynamics of materials under space conditions, kinematics of preparation and forming process of space materials, and regulation and control of material organization and properties in space environment, has been systematically summarized, and the future development trend of this discipline has been analyzed and prospected.

Keywords: Space Materials Science; Space Environment; Ultrasonic Suspension

1. Introduction

Space materials science is a new subject field formed by the interaction of materials science and space technology. Its main research content is that in the extraordinary environment characterized by microgravity, no container, high vacuum and strong radiation in outer space, the physical and chemical properties, the law of phase transformation process, the principles of synthesis, preparation, processing and forming, and the final service performance of all kinds of materials should be developed first by using the special environmental conditions in outer space, and secondly by laying a solid scientific foundation for the space application of all kinds of materials. Material science is an experimental science closely combined with engineering technology, and it is necessary to carry out space science experiments of large satellite systems. However, space experiments are not only subject to high costs, but also limited flight opportunities. Therefore, it may be the optimal way for the development of space materials science that the space experiment of simulating dragon painting on the ground is clear. Manned space flight has flourished in the past 50 years, which has promoted the emergence and rise of space materials science.

2. Cross-integration of space environment and materials science

2.1 The physical and chemical characteristics of the space environment

In a broad sense, space environment, including solar system and even cosmic environment, is the main tool for human beings to carry out space activities and explore the universe. Usually, the space environment is defined as the inside and outside of spacecraft orbiting the earth and the related environment that affects it. The physical and chemical characteristics of space environm-

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ent directly affect the on-orbit service performance and life of spacecraft materials. At the same time, it also provides a unique way to study the mechanism of condensation, flow and burning, and to develop new materials, which is an important condition for carrying out scientific research on space materials. The characteristics of space environment mainly include microgravity and containerless state, high vacuum, extreme temperature alternation, space radiation and atomic oxygen, *etc.*

2.2 Microgravity and container-free state

Orbiting spacecraft can't reach absolute weightlessness but is in microgravity under the disturbance caused by various effects. These resistances can be divided into residual forces caused by gravity gradient outside the centroid, residual external forces such as rarefaction and Ota radiation pressure, internal forces caused by mass distribution changes caused by mechanical components and astronauts' movements, *etc.* Based on these conditions, the microgravity level in the space station is about 10 g, where G is the ground standard gravity acceleration. Under microgravity, convection caused by density difference disappears, stokes motion is greatly weakened, and Marangoni convection caused by surface tension gradient is highlighted. In this environment, convection transport of heat and mass is restrained, crystal growth process is mainly controlled by diffusion process, and hydrostatic pressure in melt disappears, which makes surface and interfacial tension play a major role. Therefore, the shape of liquid is only restricted by surface tension, and wall contact can be avoided with only a small positioning force, thus realizing the material's non-containment state.

2.3 High vacuum and alternating temperature

The atmospheric pressure decreases with the distance from the ground. In the low Earth orbit where the space station is running, the atmosphere is very thin, which is considered to be a high vacuum environment. The atmospheric pressure is about 10-5~10 Pa. Because of the lack of the atmosphere blocking the radiation, the spacecraft is completely exposed to the radiation environment. Because of the lack of the atmosphere for heat transfer and heat dissipation, the temperature of the spacecraft can be as high as 100~130 ℃ when it is exposed to direct sunlight during flight. When the sun is not shining, the temperature is lower than -150~-200 ℃. In high vacuum environment, the spacecraft itself can only exchange heat through conduction between different components and radiation with the surrounding environment, which puts forward higher requirements for the design of spacecraft structure and coating materials. The radiation received by spacecraft mainly comes from solar cosmic rays and galactic cosmic rays, such as gamma rays, X rays, ultraviolet rays, *etc.* Solar cosmic rays and galactic cosmic rays are mainly composed of protons, electrons, ammonia nuclei, *etc.* Therefore, the space radiation environment is actually composed of various high-energy particles, that is, radioactive particles captured by the earth's magnetic field. These radioactive particles will have an impact on the spacecraft when it passes through the radiation belt. If the solar proton event occurs, the radiation amount will increase significantly in a short time. The complex composition of cosmic rays creates conditions for research in radiation biology and other related fields. At the same time, it is also of great significance to the research of space application materials and life sciences under extreme conditions. Atomic oxygen refers to the active gas existing as atomic oxygen in low Earth orbit. When it comes into contact with spacecraft, it constantly erodes the surface and oxidizes it, which directly affects the service performance of spacecraft materials. Shen Zhigang *et al*. have studied the atomic oxygen denudation effect of polyimide and other polymer coating film materials by using filament electromagnetic field constraint ground simulation equipment. The experimental data are basically consistent with the experimental results of foreign space flight exposure.

3. Physical and chemical properties and phase transition mechanism of materials under space conditions

3.1 The microstructure of liquid alloy

In the solidification stage of materials, the competition nucleation and growth between phases, the microstructure and structural defects of materials are closely related to the microstructure of their initial liquid. The special space environment can make the liquid alloy in thermodynamic metastable state, which provides favorable conditions for the study of the liquid structure and thermophysical properties of supercooled melt. The in-depth study of the microstructure of liquid alloy is of great significance for understanding the macroscopic properties such as material preparation, liquid-solid phase transition and crystal growth, and is also an important research content of space materials science.

3.2 High energy ray diffraction analysis

X-ray emission, synchrotron radiation X-ray emission, X-ray absorption spectrum and neutron emission are important methods to study the microstructure of liquid metal, which provide solid experimental data for the development of melt structure theory. Under the condition of no container, supercooled liquid metal can keep metastable melt state in a certain temperature range below melting point without crystallization. Kelton and Hyers *et al*. used X-ray diffraction and electrostatic suspension to study the structural evolution of suspended liquid melt. They found that the number of icosahedral ordered structures in liquid metal increased with the increase of supercooling, which also caused the nonlinear change of surface tension of high temperature liquid metal. Jacobs *et al*. studied the liquid structure of Co-Pd alloy melt by combining electromagnetic levitation and synchrotron radiation light source technology, measured the variation of nearest neighbor distance of Co-Co and Co-Pd atoms with temperature, and gave the Debye-Wal factor.

Orders *et al*. studied the microstructure characteristics of liquid Zr4Ni36 alloy by neutron scattering method, and found that electrostatic suspension has higher sensitivity and accuracy by comparing the changes of structure factor function under electrostatic suspension and electromagnetic suspension, and the secondary scattering effect brought by electromagnetic suspension coil has certain influence on the accuracy of measurement results, so it is proposed that the combination of electrostatic suspension and neutron emission is an effective method for the study of metastable melt with wide temperature range and high activity. Webers *et al*. used pneumatic suspension and laser heating combined with high energy X-ray diffraction technology to study the microstructure of various oxide melts, and measured the microstructure of Lu_2O_3 and other nuclear materials at high temperature in solid and molten state in real time. Yavaris *et al*. studied the evolution law of liquid structure during glass transition of zrCu-A alloy. Fischer and Skinner *et al*. studied the microstructure characteristics of oxide glass under pneumatic suspension. Ennes *et al*. studied the structural evolution of protein by ultrasonic suspension method combined with neutron small angle scattering and synchrotron radiation circular dichroism. With the evaporation of suspension droplets, the convection effect inside the droplets effectively inhibited the aggregation of protein molecules, and the ultrasonic field also caused protein denaturation and phase transition. They pointed out that this diversified method has opened up a new way for the study of material self-organization and crystallization kinetics in biomedical field. Benmore *et al*. proposed that ultrasonic suspension method can prepare various organic molecular compounds or amorphous solid structures of drugs, which is expected to be applied to the medical field of new drug research and development.

3.3 Numerical simulation research

Based on the experimental results of density measurement of Zr-Nb liquid alloy under electrostatic suspension, the molecular dynamics potential function is modified, and the molecular dynamics simulation of liquid alloy is carried out. It is found that with the decrease of temperature and the increase of Nb content, The microstructure order of liquid Zr-Nb alloy improved. Saboungi *et al*. studied the microstructure characteristics of supercooled liquid S by combining ab initio molecular dynamics and X-ray shooting experiment, and found that the atomic coordination number decreased with the decrease of melt temperature, and the liquid-liquid structure of supercooled Si melt changed at 1458 K to form tetrahedral ordered structure. Webers *et al*. studied the liquid structure of GeTe phase change memory material by using neutron shooting technology and ab initio molecular dynamics method, and found octahedral and tetrahedral with octahedral order as the main one.

3.4 Heat transfer process

As an important space simulation technology, the heat transfer process of falling pipe free fall method has attracted wide attention of researchers. The heat transfer process of alloy droplets was studied by combining Newton heat transfer model with classical heat conduction equation, and the thermophysical properties of liquid metal and cooling gas and the effect of droplet size on the heat transfer process were systematically analyzed. The cooling rate and internal temperature difference of typical metal droplets such as Al, Cu, T and Z were calculated under argon and nitrogen environment. The researchers also studied the laws of heat and mass transfer and melt convection by using the ground simulation space-free experiment method. In the ultrasonic suspension process, the temperature field of alloy melt is related to the deformation degree of liquid droplets. The alloy melt is ellipsoidal or round cake under the action of acoustic radiation pressure, and the surface temperature keeps rising along the equator to the poles. Abe *et al*. studied the heat exchange coefficient and thermal boundary layer thickness of water, ethanol and ethanol solution under ultrasonic long floating conditions. At the same time, the influence law of external convection on heat transfer process was explored, and the temperature field inside various electrostatic suspension droplets under microgravity and gravity conditions was numerically simulated. It was found that the droplet temperature decreased from two poles to equator, and the surface tension gradient caused by temperature gradient was the main reason for the formation of convection inside droplets. At the same time, the heat exchange inside droplets was mainly heat conduction, and the influence of heat convection on heat transfer behavior was relatively small. The temperature difference and convection velocity inside the droplets are increasing, the temperature difference inside Z reaches 74 K, and the maximum convection velocity is 25.41 cm/s. Further, a mathematical model describing the heat transfer process of electrostatically suspended metal melt is put forward, which takes into account the heat conduction inside the melt, the radiation heat dissipation on the melt surface and the complex boundary conditions of suspended melt with any shape. The cooling curves of droplets with different shapes, metals and alloys are measured experimentally, and the experimental data are in good agreement with the calculated results.

4. Conclusion

Deep space exploration and landing on the moon are becoming one of the main themes of space science and technology in the 21st century, which will break through the constraint that space materials science experiments depend on low Earth orbit. In addition, deep exploration and deep sea exploration also provide an alternative space environment with reverse extension for materials science research. Therefore, it can be expected that space materials science will present a new trend of multidimensional development in the future. The important progress of human civilization is always accompanied by the synchronous transformation of materials science and technology. China is gradually realizing goddess of the moon's great dream and will certainly make greater contributions to the development of space materials science in the new era.

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