

Hardcore Technology for Flexible Liquid Metal Materials -- Disruptive Innovation from Basic Liquid Metal Research

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Abstract

Liquid metals and their derivative materials are emerging functional substances that have emerged in recent years. A series of breakthrough discoveries have been made in this field, giving rise to many new material creations and applications, which are regarded as the second revolution in the use of metals by human beings. The team at the Institute of Physical and Chemical Technology of the Chinese Academy of Sciences has made disruptive technological breakthroughs in major fields such as liquid metal thermal management technology, advanced manufacturing, life and health, and flexible machines. By systematically studying the material properties and unique physicochemical behavior of liquid metal substances, the team seeks to create new scientific theories and knowledge and invent major transformative application technologies around a series of major needs. More importantly, China has taken the absolute leader in this disruptive technology, with the first patent, the first equipment, the first application, and the first paper all coming from China, and it can be said that the application of liquid metal substance science and technology is defined by China. This paper compares this research and explores the development mechanism of basic research to achieve disruptive innovation, to provide a reference for the formulation of relevant science and technology policies in China.

Keywords

Liquid Metals; Basic Research; Disruptive Technologies.

1. Introduction

Most people's first impressions of liquid metal come from the science fiction film "Terminator", where omnipotent robots are being made of liquid metal. Currently, with the advancement and development of scientific research, a great deal of liquid metal technology and the advanced equipment made from it are becoming a reality. To a large extent, liquid metals can be thought of as cutting-edge functional materials between machines and people, rich in scientific, technological, and application issues [1]. The reality of ambient liquid metals is a large class of emerging functional materials with very unique physicochemical behavior, typically gallium-based alloys, bismuth-based alloys, and their derivatives; with many novel properties, they provide important insights and rich research space for emerging frontiers of science and technology.

In recent years, thanks to the pioneering work of domestic and foreign scholars, especially Chinese research teams, in basic exploration and industrial practice, liquid metal matter science has developed from its initial coldness into a major frontier hotspot of international interest and influence. The greatest contribution has been made by the efforts of Liu Jing's team at the Institute of Physical and Chemical Technology of the Chinese Academy of Sciences (hereinafter referred to as IPC), whose members are at the forefront of both basic research and technological applications of liquid metals in the world. However, the team has also encountered many difficulties beyond scientific challenges in the R&D process. The purpose of this paper is to

dissect the basic scientific issues and typical advances in liquid metals, and to illustrate the value of this disruptive technology in spawning breakthrough science and industry, focusing on areas such as electronic information, additive manufacturing, biomedicine, and flexible robotics; and to sort out the basic research work encountered by the research team in conducting It also reviews the difficulties and obstacles encountered by the research team in their basic research work, and hopes to provide some lessons for solving such problems from the perspective of policy development.

2. The beginning of the research: liquid metal thermal management technology

Dan Shechtman, a 2011 Nobel Prize winner in chemistry and professor at the Technion-Israel Institute of Technology, has pointed out that the greatest limitation of today's technology comes mainly from the limitation of materials. The emergence of liquid metals and their derivative materials has unlocked many bottlenecks in applied technology and led to numerous industrial applications that have disrupted tradition. Since the beginning of the 21st century, Chinese research teams have played a systematic and pioneering role in this major scientific and technological field, revealing many new scientific phenomena, fundamental effects, and transformative applications of liquid metals; leading to the formation of a series of high-tech industries, and proposing and promoting the creation of a "liquid metal valley" and a new industry of liquid metals. and development of a new liquid metal industry [2].

However, the disruptive technology started with thermal management.

2.1. Moore's Law chip "thermal barrier" problem

With the rapid development of the electronics industry and the semiconductor industry, all kinds of electronic chips continue to develop towards miniaturization and increasing integration. At the same time, the increased functionality and enhanced performance of chips require further enhancement of their computing frequency

In the 1960s, Gordon Moore, one of the founders of Intel, predicted that "the number of transistors and resistors integrated on a semiconductor chip will increase by a factor of one every 18 months", the famous "Moore's Law " .

"Moore's Law" has successfully dominated the development of the electronics industry for nearly 50 years. However, the development of highly integrated chips inevitably brings a problem is that the chip heat problem is increasingly serious. In the process of chip work, part of the electrical energy will be converted into heat, these heat if not dissipated in time, the chip temperature will continue to rise. High temperatures can lead to chip performance degradation, increased failure rate, life decay, and even cause safety accidents. Generally speaking, to maintain the safe and efficient operation of the chip, its temperature should be controlled below 85°C.

The microelectronics industry is now facing a very serious problem of chip heating, in 2012 and 2016, the Nature 2 feature reports [2,3] pointed out that the "thermal barrier" problem has become one of the main challenges impeding the development of computer chips to higher performance, the development of high-performance chip cooling technology is imminent. The rapid development of space technology has put forward a large number of high heat flow density cooling requirements for aerospace electronics and components, such as CCD cameras, laser altimeters, spectrometers, and so on. At the same time, due to the special nature of their use environment, the need to maintain a constant operating temperature in an environment of dramatic temperature fluctuations, and there are volume and weight restrictions on the heat sink, which further increases the difficulty of its heat dissipation. In addition, there are many power electronic devices or equipment that also face high power and high heat flow heat

problems, such as high-power LED, concentrating solar cells, high-power laser chips, insulated gate bipolar transistor (IGBT) electrical converters, X-ray bulbs, engines, etc... It is no exaggeration to say that the development of high-performance cooling technology is an important prerequisite to guarantee the safe and efficient operation of these devices and the development to higher performance.

2.2. Development of heat dissipation technology

The increasing demand for heat dissipation is driving the rapid development of cooling technology. Air cooling (including air natural convection cooling and forced convection air cooling) is the current cooling method used in many low-power electronic devices, with the advantages of simplicity, reliability, and low cost, but its cooling capacity is very limited, generally only for heat flow density $<10\text{W}/\text{cm}^2$

The situation. Heat pipe is a highly efficient heat transfer element, invented in 1963 by George Grover of Los Alamos (Los Alamos) National Laboratory, which has a very high equivalent thermal conductivity (generally in the order of $10^4\text{W}/\text{m}\cdot\text{K}$), two orders of magnitude higher than the thermal conductivity of commonly used high thermal conductivity metals such as aluminum and copper. Heat pipe-based cooling technology is currently the mainstream cooling technology for notebook computers, usually, the heat dissipation heat flow density is in the range of $10^1\sim10^2\text{W}/\text{cm}^2$. When faced with higher heat flow densities, such as $10^2\sim10^3\text{W}/\text{cm}^2$, liquid cooling measures, including single-phase convection liquid cooling and two-phase boiling cooling, are often required. Since its [2] introduction by Tuckerman and Pease in 1981, microfluidic liquid cooling with water as the main cooling substance has increasingly become a hot topic of interest for researchers [2,3], especially nanofluidic microfluidic convection cooling techniques with the addition of nanoparticles to enhance their heat transfer [2]. Although water cooling technology has great advantages in dealing with high heat flow cooling, it still faces some problems: 1) the thermal conductivity of water is low, only $0.6\text{W}/(\text{m}\cdot\text{K})$ (20°C), which leads to its poor convective heat transfer capability; for this reason, people have developed microflow channel technology, but this, in turn, brings a problem of huge flow resistance of the cold plate, the corresponding high power consumption of the pump, the risk of leakage, and the tendency of flow channel blockage. 2) Water has a limited operating temperature range and will boil at temperatures above 100°C , making it less suitable for heat transfer requirements across 100°C .

Theoretically, to enhance the convection cooling capacity of the cold plate, two aspects can generally be considered: 1) designing a reasonable cold plate structure to obtain better thermal performance while the flow resistance is in an acceptable range; 2) using a cooling workpiece with good thermal properties. For the former, researchers have made a lot of research work. For the latter, it has been difficult to find a suitable cooling medium. It is in this context that room-temperature liquid metal cooling technology was conceived.

2.3. System-complete liquid metal high-performance heat dissipation technology: from basic research to application

In 2002, Liu Jing of the Institute of Physical and Chemical Technology of the Chinese Academy of Sciences proposed the use of liquid metal as a coolant for cooling high-performance computer chips to solve the increasingly serious problem of "thermal barrier" [2]. The liquid metal mentioned here is different from the traditional mercury and alkali metal materials, mainly refers to gallium and its alloys (such as gallium-indium alloy, gallium-indium-tin alloy, etc.) and bismuth-based alloys (such as bismuth-indium-tin alloy), which are safe and non-toxic low-melting-point metal materials with the melting point near room temperature. The introduction of room temperature liquid metal represented by gallium into the cooling of electronic devices is a fundamental conceptual breakthrough, changing people's understanding

of traditional liquid metal materials, and thus opening the door to liquid metal in the field of consumer electronics cooling.

In 2004, Nanocoolers, Inc. was awarded tens of millions of dollars to research liquid metal chip cooling technology [2] and released a commercial liquid metal CPU cooler in 2005 [2]. 2009, Aqwest LLC, Inc. researched liquid metal cooling technology for laser-pumped diodes. In 2010, the Journal of Electronic Packaging, the journal of the American Society of Mechanical Engineers (ASME), awarded the only paper of the year for the best paper on liquid metal cooling technology, "Design of practical liquid metal cooling device for heat dissipation of high performance CPUs [2]"; the paper's corresponding author is Jing Liu, and the first author is his Ph.D. student Yueguang Deng. 2013, the U.S. In 2014, the National Aeronautics and Space Administration (NASA) listed liquid metal cooling technology as a future frontier research direction. As you can see, this technology, born and developed in China, has attracted a lot of attention from the United States, a technological powerhouse, and the competition between the two sides has intensified in recent years.

Since the proposal of liquid metal chip cooling technology in 2002, Jing Liu's team has been committed to promoting the development of this technology and has made a lot of original innovative work. After years of efforts, the team has established a perfect liquid metal material preparation and physical characterization technology as well as cooling system related theoretical analysis, experimental testing, numerical simulation, and optimization design methods, published nearly 100 academic papers in authoritative academic journals and conferences at home and abroad, and applied for more than 100 national patents for related technologies. In addition to academic research, Liu Jing's team has also continued to promote the process of industrialization.

3. "The will of the beast": liquid metal additive manufacturing technology

During the team's development of liquid metal heat dissipation, the material fell on the benchtop of the experiment many times, and when the researchers gently wiped it with a glove, they found that the liquid droplets of liquid metal became a continuous line, and the researchers thus thought that liquid metal might be able to act as a conductor, based on such a chance discovery that led to the beginning of liquid metal printed electronics.

3.1. Liquid Metal Printed Electronics

Printed electronics is an emerging electronic additive manufacturing technology based on the principle of printing, which has unparalleled advantages over traditional electronic processing methods in terms of large area, flexibility, personalization, and low-cost manufacturing of electronics. Typical conductive inks used in printed electronics are usually divided into three categories: carbon, polymer, and metal conductive inks, however, they still need to be printed with the help of a high-temperature post-treatment process to further enhance the electrical conductivity of the print and ink and operational reliability, the steps are slightly cumbersome; and because the corresponding nanomaterials and ink formulation is more complex, also increases the cost of use. Liquid metal, as a new class of e-printing ink, is becoming an important research area in recent years, which has the unique advantages of high electrical conductivity, simple preparation, and no post-processing.

3.2. Liquid metal desktop electronic circuit printer

The research team has accordingly built a liquid metal printer, which is directly connected to a computer and prints on the spot according to the images entered by the research team, very quickly and easily. Based on this original idea, the team developed a desktop electronic circuit printer, which was marketed five or six years ago and has been purchased by numerous research institutions, both for cutting-edge research and for education and training. But liquid

metal also has disadvantages, tends to become ball-shaped, not what body can be hit on. The research team hopes that leaves, paper, glass, just spray on the circuit can be obtained, to achieve such a goal, the research team from the specific mechanism, the use of liquid metal surface oxide layer, control the thickness of the oxide layer and the viscosity between the oxide layer and the mechanism. The research team developed the liquid metal inkjet printer based on such a principle. The research team heated to 80 degrees, room temperature can be cured directly into shape after printing is not afraid to touch, the melting point is 60 degrees, after hitting the room temperature of more than 20 degrees, can be cured directly, can be used directly. Can also be applied to do a double-layer circuit, the connection between the layer and the layer with the same metal to connect, is based on such an idea research team developed a liquid metal double-layer printer.

3.3. Liquid Metal In-Situ Rapid Printer

The above-mentioned types of printers, and then further development, the printing step is a point scan, the research team wanted to be faster, to achieve the innovation of second printing, the research team used liquid metal, in the liquid metal mixed with some oxides, its viscosity will be particularly good, this is an ordinary laser printer, first go to print the background, first print out the unwanted background, and then put it between the two rollers, the Dipped in liquid metal, this shows a very complex circuit the size of A4 paper, which can be obtained within 3 seconds, and still bendable. The research team has also developed a printer for Class B metal 3D, which is not yet available.

3.4. Liquid metal 3D printing technology and equipment

3D printing (also known as "additive manufacturing") as an advanced manufacturing technology, through the "layered manufacturing, incremental forming" processing method to meet the personalized and customized needs of physical objects, is considered to be the "third It is considered to be one of the key drivers of the "Third Industrial Revolution". With the release of the first national 3D printing development plan "National Additive Manufacturing Industry Development Promotion Plan (2015-2016)" and the introduction of the "Made in China 2025" planning outline, the technology is based on digital manufacturing and design, and the deep integration with Internet business services and advanced materials technology will definitely bring disruptive changes to the traditional manufacturing industry. . Accelerating the development and industrialization application of 3D printing technology is of great significance to enhance the independent innovation capability of China's manufacturing industry, seize the high ground of future science and technology and industry, promote the transformation and upgrading of China's manufacturing industry and the transformation of economic development mode, and realize the construction goal of manufacturing power.

3D printing technology of metal materials, as the most cutting-edge and most engineering application potential technology in the 3D printing manufacturing system, is one of the important development directions to accelerate the development of new technologies and equipment for intelligent manufacturing. Among them, special metal printing materials, process technology level, and manufacturing equipment and core devices of innovation, research and development and transformation of results is the development of 3D printing advanced manufacturing technology of key technology nodes.

The Laboratory of Low-Temperature Biology and Medicine Research, Institute of Physical and Chemical Technology, Chinese Academy of Sciences, with the strategic positioning of high technology innovation and transfer of results, has initiated research on liquid metal since 2002, and in recent years has carried out a series of research and development on low melting point metal 3D printing methods, processes and equipment using room temperature liquid metal as the forming material, forming a series of unique core technology patents, and promoting the technology to the market, successfully We have realized the engineering application of liquid

metal printing results and formed a series of "Dream Ink" liquid metal 3D printing ink materials and equipment with independent intellectual property rights. In the area of electronic circuit printing, the laboratory has proposed the academic idea and technical system of liquid metal printed electronics [2] successfully realized the use of liquid metal and molten metal to directly print circuits and functional devices on the surface of paper, skin, and other flexible materials by studying the adhesion between low-melting point metals and different substrate materials [2,3,4], and has made fruitful exploration and accumulated experience in 3D printing and forming for wearable electronic products and flexible bendable circuits. In terms of 3D printing of terminal functional electronic devices, the laboratory has proposed a basic method of 3D printing in the liquid-phase cooling environment to address the problems of high temperature, slow solidification, and slow printing speed of traditional metal 3D printing, which [2] breaks through the inherent forming scope of traditional 3D printing technology and provides the possibility of rapid forming of terminal functional devices at room temperature in the future. It provides the possibility of rapid forming of end-use functional devices at room temperature. In addition, the lab has also pioneered and realized the simultaneous 3D printing of liquid metal and non-metal materials [2], providing the possibility of direct printing and assembly of all units of functional devices in the future. With the continuous development of 3D printing technology, as well as the national efforts to promote the transformation and upgrading of manufacturing industries and accelerate the industrial formation and orderly development of 3D printing technology, the laboratory will continue to carry out basic exploration and technological innovation around the frontier of forming theory and technology for 3D printing of room temperature or low melting point metals and focus on promoting the industrialization and industrial application of related technologies to help advance the development of national 3D printing technology.

3.5. A Glimpse of Liquid Metal Printed Electronics Applications

With the support of liquid metal printed electronics technology, it will bring many conveniences to our learning life. For example, in the circuit classroom, the teacher can show the classroom content vividly and timely through the liquid metal printed electronics technology. Students can also experiment with circuits immediately after the teacher's lecture. In the future, the research team will use liquid metal printing technology to do the collection and sending of information using the Internet of Things to truly realize the dream of the interconnection of all things.

Currently, the research team is using liquid metal printing technology in apparel design to achieve the pursuit of science with beauty. Besides that, it can also do dynamic advertising design. Many artists can also use liquid metal to make paintings, and the research team has many liquid metal artifacts that have been customized for the Tsinghua University Museum. In the centennial celebration of Tsinghua University, the research team made the moonlight on the river pond for it, and the centennial lecture hall achieved very good results. At the same time, the research team also perfectly combines liquid metal printing technology and silk to achieve the fusion of cutting-edge technology and fashion.

4. Deliberate: liquid metal biomaterials and technologies

In the field of biomedical and health technologies, unique liquid metals have brought about conceptual changes. The research team has pioneered the use of liquid metals to solve a series of major biomedical problems and bottlenecks, systematically proposing and building a new field of liquid metal biomedical materials science [2,3] research results have triggered international repercussions. Among them, liquid metal neural connectivity and repair modulation technology is regarded as an [2] "astounding medical breakthrough" due to its originality, which has led to a series of neural modulation technologies [2].

Prior to this, the research team had an original starting point for wanting to combine the conductivity of liquid metals with medicine, such as plaster bandages. Most existing casts are disposable, solid encasements that are extremely inconvenient for patients to wear and impossible for doctors to medicate and photograph wounds promptly. Liquid metal-style bandages can not only be used multiple times, but their good light transmission does not hinder treatment. There are also bioelectrodes that are solid, can not achieve a good fit, liquid metal has natural properties, more superior, using liquid metal to do a neural connection work, a step forward, just showed a dying frog, the research team put flexible electrodes into its sciatic nerve, can appear to leap behavior, of course, this is still quite controversial, from the development point of view or do a very good This is still quite controversial, but from the development point of view, it is still a good attempt.

5. Serendipitous discovery: liquid metal flexible intelligent robots

It is the dream of the world's scientific and engineering communities to design a flexible machine that can freely transform between different forms in a controlled manner and be used to perform more specific and complex tasks in place of humans. For example, in earthquake relief or special operations, such robots could deform at the right time, move through tight spaces, and regain their original shape as needed to continue performing their tasks. Academics generally believe that a breakthrough in soft-body robotics will significantly impact high-end manufacturing, medical rehabilitation, defense equipment, and other fields. Related R&D activities are in full swing, with NSF-supported soft robotics projects reaching \$26 million in 2017.

Starting from the concept of building a new system, the research team has proposed a different technological path for liquid metal soft robotics [2][3], and gradually developed a corresponding theoretical and technological system in terms of materials, devices, and systems [2]. One of the landmark advances is the first time to reveal a series of large-scale deformation, rotation, directional motion and merging, fracture-remerging behaviors of liquid metal under the regulation of the electric field [2], which becomes the beginning of subsequent research on liquid metal deformable robots. An unusually unique phenomenon and the mechanism was further discovered [2,3], whereby liquid metals can form self-driven, fully flexible machines by engulfing trace amounts of aluminum, with speeds of centimeters per second and running times of several hours, enabling autonomous motion without external power. This cluster of micro-motors of self-driven liquid metals can form high-speed synergistic motions in an electric field. The above findings lay an important theoretical foundation for the development of practical smart motors, vascular robots, fluid pumping systems, flexible actuators, and even more complex liquid metal robots. By combining liquid metal and rigid materials, solid-liquid combination machines can also be realized. Electrically controlled, deformable, and rotatable "liquid metal wheels" can drive 3D printed miniature vehicles for travel, acceleration, and more complex movements. The research also revealed the ability of the liquid metal to be shaped stably in any shape on graphite surfaces, allowing the liquid metal to climb against gravity. Programming liquid machine cells in groups would establish a viable technological pathway to controllable, flexible, and intelligent robots, which would change the technological form of traditional robots.

Overall, liquid metals have led to a new concept of deformable machines, which will significantly accelerate the development of flexible and intelligent machines. In view of the breakthrough of these discoveries, the corresponding results have generated a large international response and have been reviewed by Nature, NatureMaterials, ScienceNews, NewScientist, ChemistryWorld, etc., and liquid metal robotics has been listed as one of the ten most promising directions in the field of robotics.

Liu Jing team first did the work of neural connectivity with liquid metal, in that work, there is decomposing mass in the organism, the research team took the liquid metal and the electrode to give him a stimulus, and the electrolyte in the organism, the three factors integrated, the research team found that the liquid of the liquid metal can move directionally, the research team started the chapter of robotics, transplanting the three elements into a glass vessel, which can found that either the liquid base or the thin film could be transformed from two-dimensional to three-dimensional. This deformation has to be reversible, and the research team manipulated in electric and chemical fields together, which can be easily achieved by laying flat and recycling. In addition to deformation, one side can deform, be able to move on the other side, and can easily pass through slits tens of times smaller than its diameter under the electric field. Liquid metal surface tension is relatively large, in most cases is to become a liquid base, the research team added a fast graphite plate, the surface will be oxides, increasing the adhesion, in the electric field of traction can be like a caterpillar creeping forward. All other external fields are possible except the electric field, shown here with a small droplet moving under a magnetic field. Solid magnets, the magnetic poles are not controllable, but for liquid metals, this regulation is very easy, that is, adaptive change, deformable and controllable, is one of its greatest features. This is the thermal field, the research team put it together with the polymer material, through the laser external field stimulation, hit where, where can bulge .

This is made in the shape of an octopus. It's quite interesting to see how the material inside leaves a few tears when the temperature is particularly high. Further, just now it was all kinds of fields, can movement be achieved without an external field as well? The answer is of course yes, it is possible to achieve a completely self-driven motion without an external field, which is a process of eating. This is among various shapes of orbits, and it is possible to achieve directed motion as well. When it encounters a large resistance, it may pause a little, as if thinking about how to go next, a bit like a biological body. It is also possible to achieve the transition between different forms and sizes, which is a bit like the Monkey King plucking a sweat hair and giving birth to millions of children and grandchildren, which turn from small to big and finally become a complete liquid like a snake eating beans.

This experimental discovery was accidental, because at that time the research team put the liquid metal that had eaten aluminum on the graphite plate, and would find that it could go towards trilobites, which is a more primitive creature, to produce tail feet. At that time a CCTV promo wanted to repeat the experiment, so I sent one of my students, who was not the first time to do this experiment, to repeat the experiment, adding a little more aluminum during the experiment, and it was found that in addition to deformation it could also change color.

The research team later found through careful study that the color change is closely related to the thickness of the oxide layer, the research team on the one hand by regulating the substrate, that is, adding a graphite plate, so that it can become a uniform color. Because it is directly related to the thickness of the oxide layer, and the electric field can regulate the thickness of the oxide layer, the research team designed different electrodes to induce it, it can produce a variety of rainbow colors, and this color is not added to the color, but the structure of its color.

The human body is all made of carbon-based materials that have evolved over tens of billions of years to become what it is today. Liquid metal robots have taken on the characteristics of simple biome-like organisms since their inception, which is only five or six years from the earliest discoveries of liquid metal electronically controlled robots, and the research team hopes that in the future it could achieve an all-metal-based life like The Terminator, which might be worth looking forward to.

6. Research team

The research on liquid metals by Jing Liu's team at the Institute of Physical and Chemical Sciences is typical of free exploratory applied basic research. The research team makes experiments while discovering and then pioneering in a targeted manner. The research idea of first making key technological breakthroughs in liquid metal research, and then further pushing it to practical market applications, is practical and scientific. Disruptive technologies are not planned to come, and Liu Jing's team has been doing hard work from its inception to now. According to team members' recollection, there was often a lack of R&D funding during the long research process. Due to the evasive mechanism of the Nature Foundation Committee's project evaluation, liquid metals could not be established at the beginning of the project as few people at home and abroad were doing it. As a result, the research team has not received any major national projects, key R&D programs of the Ministry of Science and Technology, etc... The team members could only receive some relatively small financial support. After investigating the liquid metal research lab, the then president of the Chinese Academy of Sciences, Academician Bai Chunli, allocated 4.5 million to the research team through the Dean's Fund, which was the most funding the research team had ever received. Even though the research team had been doing medical devices with broad commercial prospects for many years, there were no particularly large grants. To make matters more difficult, there are also some irrational systems within the Institute of Physical Chemistry. In particular, the phenomenon of "those without hats wanting to support those with hats" is particularly serious, as Jing Liu's team is already facing a shortage of funds when carrying out the technology, and the results and proceeds from industrialization also need to be used as management fees by the Stock Exchange to support "those with hats" to publish papers without fear. This is a huge blow to the enthusiasm of the "non-hat" researchers. In addition, many researchers in the Institute of Physics and Chemistry also face problems in life, such as children's schooling, which is a very important reason for the brain drain.

7. Concluding remarks

At present, liquid metal R&D and applications are gradually moving into the fast lane. Compared with the international enthusiastic situation of liquid metal R&D, the domestic R&D teams and enterprises entering this emerging field have not yet formed sufficient volume, largely due to the lack of relevant policy support, China has a first-mover advantage in liquid metal research, but the policy response is relatively slow, and the existing leading edge is likely to be overtaken. At the same time, the R&D experience of applied basic research can also be learned from the R&D process of liquid metals.

(1) Disruptive technologies are not planned, they can be encountered but not sought, they are serendipitous and unique. They belong to researchers who are curious, innovative, and good at catching inspiration.

(2) Disruptive technologies are not adaptations of inherited innovations, stemming from original innovations, and are discoveries and breakthroughs in important fundamental theories and applied foundations.

(3) Important basic research with generic commonalities that can be integrated with existing technological needs to achieve universal applicability.

(4) Young researchers and projects with original innovation should be able to provide stable support, which requires the Fund Committee and other relevant research fund management departments to be able to carry out reforms in the relevant systems, such as the contradiction between original innovation projects and the avoidance mechanism, and the polarization caused by the subject system.

(5) In terms of industrial market cultivation, national and local industrial funds and support policies can be established; accelerating the deployment of liquid metal industry clusters, promoting the transformation, upgrading, and leapfrog development of the manufacturing industries concerned; guiding the promotion and application of new liquid metal products, maintaining the frontier technology research and development, the trial and error of new products and the integration of emerging markets and even the formation of a virtuous interaction.

Liquid metals create significant opportunities for the transformative development of many frontier technologies and are extremely driving. It is advisable to carry out a series of soft topics and strategic research at the macro research level to scientifically foresee the key role of this emerging material for electronic information, advanced manufacturing, defense equipment, medical health, flexible intelligent robotics, and other fields, to promote the progress of national frontier science and technology, and to promote the development of new industrial systems.

In the past, mankind used the Stone Age, the Bronze Age, the Iron Age, and the New Material Age to portray the development of society, and it can be seen that materials play a pivotal role in the development of human civilization and the industrial economy. Mankind will likely enter the age of liquid metal in the future, and the discovery of more liquid metal materials, will further change people's cognition, change scientific concepts, change the level of technology, and ultimately change the level of the material civilization of human society.

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