Research of Thin Film Thermocouple Based on MEMS for Temperature Measurement on Spacecraft Surface

ZhenWei Li, ZeYuan Liu, Chang Liu and Fang Han
Beijing Institute of Spacecraft Environment Engineering, Beijing 100094, China
13502836@qq.com

Keywords: MEMS (Micro-Electro-Mechanical-Systems), thin film thermocouple, the measurement of spacecraft surface transient temperature, physical test.

Abstract: The paper introduces the technology of MEMS and its advantages in the manufacture of aerospace sensors. According to the requirements of spacecraft surface temperature measurement, a K-type (NiCr/NiSi) thin film thermocouple is designed. The graphic process design of thin film thermocouple is studied, including thermal junction and thin film lead wires. The test shows that the response time of the thin film thermocouple is shorter and the relative error is smaller compared with the traditional thermocouple.

1 INTRODUCTION

The MEMS (Micro-Electro-Mechanical-System) is based on the micron/nanometre technology, and was applied to the design, processing, manufacturing, measurement and control of micron/nanometre materials. It's an intelligent extension of integrated circuit technology. The MEMS has the advantages of miniaturization, integration, low energy consumption, low cost, high accuracy, long life and dynamic properties(Zhu,2013). With the above advantages, the MEMS becomes the ideal device in space application field. In the future, the space exploration will focus on the cost and goal of task. In order to save cost, the future trend will be the MEMS devices replace the heavy weight devices on the space carrier, the actual loads on the communication and navigation platform. Furthermore, it will replace the complete subsystems, such as attitude sensor, attitude controller, phased-array antenna, earth sensor and optical switch. Compared with the traditional solutions, the size and quality of MEMS devices can be significantly decreased. Some of the MEMS devices(Wu, 2012) which have been used in space are displayed in Table 1.

Table 1: The MEMS devices used in space and its technical maturity.

MEMS device name	Flight mission	Technical maturity
Accelerometers ， gyroscopes	NASA regular flight	High-level
Pressure sensor	Rocket normal flight	High-level
Magnetometer	Cube satellite flight	High-level
Atomic force mi cro-scope	The "Phoenix" mission of NASA in 2008	Advanced-level
Solar sensor	The "Delfi 3C" mission in 2008	Advanced-level
Microfluidic sensor	The "GeneSat" satellite mission of NASA	Middle-level
Bolometer	The "Planck" mission of ESA in 2009	Middle-level
Thermal controller	The task of "Space Technology 5"of NASA in2006	Middle-level
Micro optical electromechanic al system	Used in Jame Webb Space Telescope in 2013	Intermediat e-level

With the rapid development of deep space exploration, hypersonic vehicles and space shuttle vehicles in China, the transient temperature measurement of the spacecraft surface is better required(Zhang,2013). Especially, in the process of returnable spacecraft re-entry flight, the aerodynamic heat effect of high speed friction will make the temperature of spacecraft surface rise fast(Manoj,2015). The surface temperature can better reflect the thermal characteristics of the spacecraft and its structures. It also can provide the reference data for the verification of spacecraft's

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thermal protection system. At present, the ordinary thermocouples were generally used to measure the surface temperature of spacecraft during its thermal test and flight. However, for the hypersonic and space shuttle spacecraft, the surface temperature is changed sharply. Due to the structure, heat capacity and installation mode of the ordinary thermocouples, the measurement results were obviously hysteresis and inaccurately. It can't meet the measurement requirements of the spacecraft surface transient high temperature.

To solve the above problems, the MEMS process of thin film thermocouples is researched in this paper, which can be used to measure the spacecraft surface transient high temperature. In present, the temperature sensor based on thin film thermocouple has been used in the measurement of the bullet ejected bore, the wall of internal-combustion engine, the heat flux distribution of the laser beam, and the working cutting tool successfully(Zhao,2012). However, due to the special structure of spacecraft, the thin film of thermocouple can't be pasted on the surface of test object directly. Therefore, the needle-type structure of thin film thermocouple is proposed in this paper. The high temperature resistant ceramic material is selected as the structure substrate and K-type material is selected as thermoelectric material for this type of thermocouple. Then, the thin film thermocouple was prepared on the structure substrate by magnetron sputtering technology. The thickness of this thermocouple's thermal junction is micron scale, and its capacity is much smaller than the traditional thermocouple. It can be effectively fitted to the surface of the test object, and the transient temperature up to 800℃ is measured quickly and accurately. These properties make the sensor better meet the measurement requirements of the hypersonic vehicles and space shuttle vehicles.

2 WORKING PRINCIPLE AND STRUCTURE DESIGN OF THIN FILM THERMOCOUPLE

In 1821, the German physicist Thomas Johann Seebeck found the thermocouple phenomenon, which describes that the junction of two different materials can generate voltage with the temperature changing. For the same type of thermocouple, the thermoelectric potential generated by thermocouple is proportional to the temperature difference between two thermal junctions. The relationship between the thermoelectric potential and temperature difference is described in equation (1).

$$\Delta V=\alpha_s*\Delta T \tag{1}$$

In equation (1), the ΔV is the thermoelectric potential generated by thermocouple, the ΔT is the temperature difference between two thermal junctions, and the α_s is Seebeck coefficient, whose unit is μV/K.

In the long term industrial practice, several standard thermocouples have been gradually formed, such as B-type (PtRh30-PtRh6) thermocouple, S-type (PtRhl0-Pt) thermocouple, R-type (PtRhl3-Pt) thermocouple and K-type (NiCr-NiSi) thermocouple. These thermocouples are different at thermoelectric material. In consideration of the working temperature range, the measurement accuracy and the economic cost, this paper selects the K-type thermoelectric material which conforms to the national standard to research the MEMS film technology.

In order to fit the actual conditions of the transient temperature measurement on spacecraft surface, the style of thin film thermocouple structure was designed as needle-like. As shown in Figure 1, the thermocouple structure substrate is divided into the base head and the base tailstock. First, Al_2O_3 insulation film was deposited on the surface of the thermocouple substrate that the material is high temperature resistant ceramic material. Then, the K-type thermocouple thin film was deposited on the top of substrate base head by magnetron sputtering technology. Finally, the Al_2O_3 insulation film is deposited on the thermocouple film. This insulation film can protect thermocouple film from falling off and breaking, caused by friction, scour, impact and corrosion. At the same time, it can also provide the well electrical insulation and physical protection for thermocouple film.

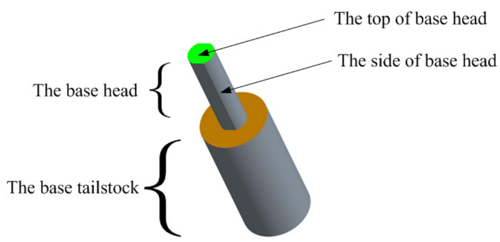


Figure 1: The structure diagram of needle-type thin film thermocouple.

The thermal junction of thermoelectric material is located at the top of base structure's head. As shown in Figure 2, the NiCr film and NiSi film were prepared on the left and right semicircular surfaces on the top of base head by the magnetron sputtering technology. The thermal junction is the core of the sensor. The thickness of the thermocouple film is about 2μm. The diameter of the isothermal surface is 50 times more than thermocouple film's thickness, while, the geometric area of thermal junction is much less than the isothermal surface. Therefore, the specific heat capacity of the thermal junction is much smaller than that of the traditional thermocouples. It can achieve the measurement of transient temperature easily. The thermal junction of the thin film thermocouple is good performances. But, the preparation process of the thin film thermocoupleis difficult.

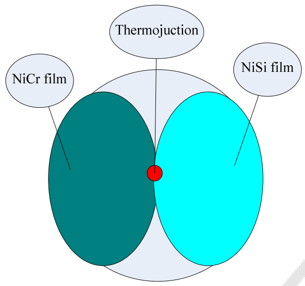


Figure 2: The thermal junction diagram of thin film thermocouple.

3 THE FABRICATION PROCESS OF THERMOCOUPLE

The k-type thin film thermocouple studied in this paper is processed by MEMS process. The MEMS microprocessing technology is an extension of traditional microelectronics technology. In the substrate selection from the traditional silicon material, expanded to ceramics, glass, plastic and other materials. MEMS microprocessing technology enables the chip processing method from 2D to 3D, through electroplating, mold, laser, corrosion and other processes. A series of MEMS processes, such as photolithography, stripping and sputtering, are used during the processing of k-type film thermocouples. The substrate of thermocouple is nonplanar substrate, with greatly processing difficulty. The special fixture is designed in this paper, and the fabrication of MEMS process, such as photolithography and sputtering of 3D unit, is realized.

3.1Target material

The electrode materials of the k-type thin film thermocouple are prepared by sputtering, and the sputtering equipment is KJLC LAB18. Sputtering particles of energy (ions, neutral atoms or molecules), such as argon ions, are used to bombard the target surface. Atoms and molecules near the target surface will get enough energy to escape from the target surface, and then deposit on the substrate of thermocouple. The purity of target material will affect the composition of the thermocouple electrode and the temperature measurement precision of the thermocouple. In this paper, the targets of $Ni_{90}Cr_{10}$, $Ni_{97}Si_3$ and Al_2O_3 with purity of 99.99% were prepared according to the atomic weight ratio, which were shown in Figure 3.

Figure 3: Sputtering targets

3.2 The technology process

Fabrication process of needle-type thin film thermocouple includes ceramic substrate production, lead wire production, thermal junction production, and the encapsulation of the lead terminal etc. In the process, each step is carried out in order.

3.2.1 Selection of the substrate material

The substrate is the basic component of the thin film thermocouple structure. Because the maximum temperature range of the film thermocouple reaches 800℃, it is necessary for the substrate material to have a high temperature resistance. In addition, in order to avoid the influence of the thermocouple temperature from the substrate, that is required to having low thermal conductivity for the substrate. This paper uses the Al_2O_3 ceramic with high heat resistance and low thermal conductivity as substrate material. As shown in Figure 4 as the substrate structure.

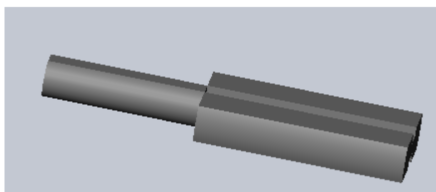


Figure 4: The structure of substrate

3.2.2 The lead terminal making

According to the thermocouple homogeneous conductor's law, if the third material in the production of lead terminals was inducted, it may cause the thermal potential of two leads different, and then cause the measurement errors. In this paper, the electrode leads are made by the same target materials as the two thermoelectric materials of the thermocouple, and then bonded to the grooves on the side of the base with high temperature ceramic glue. The surface of the electrode leads needs to be planed and polished. As shown in Figure 5 as the lead terminal making.

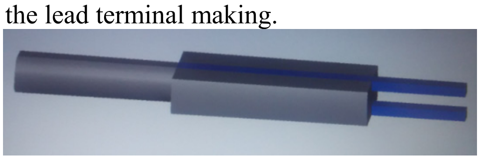


Figure 5: The lead terminal making

3.2.3 Preparation of lead wire

The commonly used methods for making the thin film lead of thermocouple are peeling and etching respectively. Special aluminum foil tape is used as the mask in the peeling method, and the design pattern of the thin film lead is transfered to the mask by stamping or laser etching process. Using the NiCr and NiSi target sputtering, film thickness is 1μm. The mask is removed to form thermal electrode film pattern. However, the change of the temperature in the sputtering process causes the change of the adhesive force between the mask and the substrate, resulting in the distortion of the mask pattern.

In order to solve the above problems, this paper uses laser etching method to make thin film. The surface of the ceramic substrate is covered by sputtering thickness of 1μm NiCr/NiSi film. The film parameters design is directly input into the laser controller to control the movement of the laser spot, and the excess film is melted away. The etching laser is produced by a 1064nm wavelength fiber laser with a moving precision of 1μm, which can ensure the high precision of lead figure. As shown in Figure 6, the width of the film lead is designed to be 250μm, and the measured width is 254.30μm.

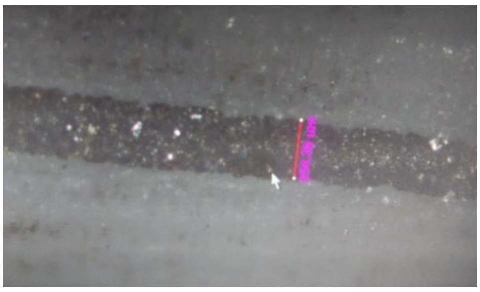


Figure 6: Thin film wire

3.2.4 Preparation of the thermal junction

The thermal junction is the most important part of the thermocouple measurement circuit, which is directly contacted with the surface of the thermometric object. The heat capacity of the thermal junction is very small, and it can quickly reach the same temperature as the surface of the thermometric object. By measuring the thermoelectric power signal produced by the Seebeck effect, surface temperature can be calculated. As we can see from Figure 2, the region of the interaction between NiCr film and NiSi film forms a thermal junction, with a diameter of 200μm and a thickness of 2μm. The mechanical mask and exposure mask methods were studied and analyzed in this paper before preparing the thermal junction. If the mechanical mask method is adopted, the SUS304 stainless steel sheet will be handled according to WEDM process of making the mask, as shown in Figure 7. Due to the edge roughness of the mechanical mask relatively large, the figure of the thermal junction is not regular enough.

Figure 7: The mechanical mask

In order to further insure the accuracy of the graphics, a special exposure mask method is developed in this paper. First, the design diagram is transferred (copied) to the film. Then, photosensitive ink or hot pressing dry film was coated on the top of the ceramic substrate. The film mask is placed on the top of ceramic column, and then exposed with UV lamp. It is melted into the developing liquid. Then the top shape has been transferred to the top of ceramic column. After the sputtering is completed, the ceramic column is put into the stripping solution or acetone solution to dissolve the ink or dry film. Finally, as shown in Figure 9, only the thermal junction film is left on the top of the ceramic.

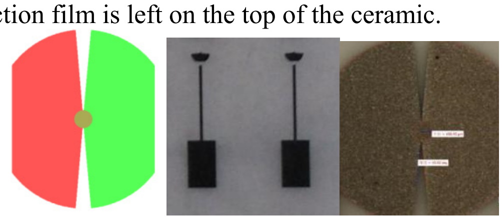


Figure 8: Thermocouple junction design

4 PHYSICAL VERIFICATION AND RESULT ANALYSIS

In order to verify the overall performance of the thin film thermocouple which was designed in this paper, a thermocouple performance testing system was developed firstly(Li,2017). As shown in Figure 9, the system consists of control computer, measuring instrument, programmable power supply, infrared lamp array, copper plate of constant temperature and graphite carpet etc. During the actual test, 8 K-type ordinary thermocouples and 2 K-type needle thin film thermocouples were installed equably on Φ200mm circle on the copper plate. The temperature of the copper plate must maintain constant in order to ensure that all thermocouples were in an uniform temperature field. The copper plate was heated by the infrared lamp array, and its target temperature was set as the average temperature value of 8 ordinary thermocouples. The thermoelectric potentials of ordinary thermocouples and needle thin film thermocouples under the same temperature field were read, and then converted into the temperature values. Comparison and analysis of the temperature measurement values between thin film thermocouple and ordinary thermocouple, the results of two thermocouples fit well, we can conclude the measurement performance of the film thermocouple under the conditions of high temperature impact and transient temperature was verified.

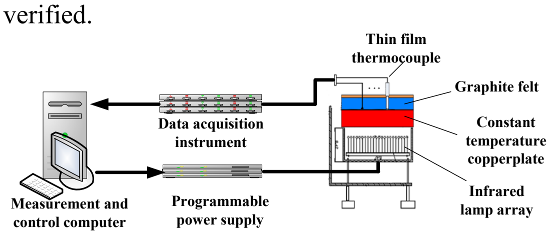


Figure 9: Performance test system for thin-film thermocouple.

In this paper, eight K-style ordinary thermocouples were named by 1# to 8#, and two K-type needle thin film thermocouples were named by 9# to 10#. In order to verify up to 800℃working temperature of the thin film thermocouple , the copper plate for the performance test system was heated up to 850℃. The excess of 50℃is used to verify the reliability of the film thermocouple. The test results of measurement points were shown in Figure 10 and Figure 11.

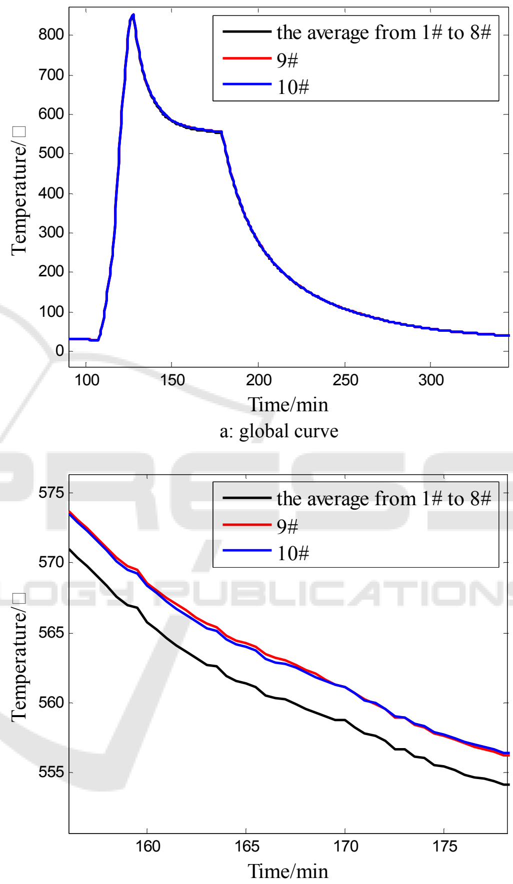
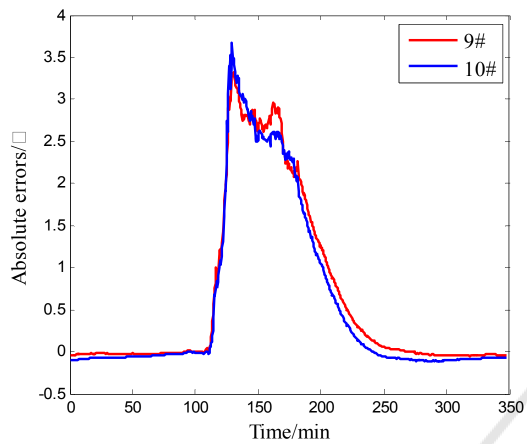


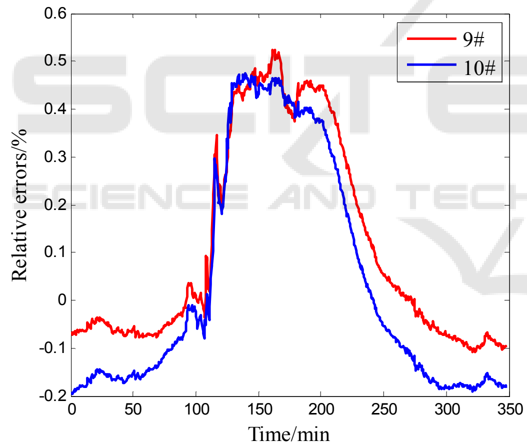
Figure 10: Temperatures of the copper plate and needle thin film thermocouples

The average temperature value of eight ordinary thermocouples and two thin film thermocouples were shown in the Figure 10. We could see from figure 10 that the copper plate was begun to heated at about 107min. And then, the temperature values of all thermocouples increased rapidly, and reached about 850℃ at about 127min. Among them, the average temperature value of eight ordinary thermocouples rose from 29.6℃ to 850.1℃ in 20 minutes, and its average temperature rise rate was

41.2℃/min, and its maximum temperature rise rate was 78.8 ℃/min. The temperature of needle thin film thermocouples rose from 29.6℃ to 853.2 ℃ in 20 minutes, and its average temperature rise rate was 41.2 ℃/min, and its maximum temperature rise rate was 78.9 ℃/min.



a: absolute errors



b: relative errors

Figure 11: Temperature measurement errors of thin-film thermocouples

For the purpose of analysis of the validity and accuracy of temperature value for the needle thin film thermocouples, the temperature values of 9# and 10# thin film thermocouple were compared with the actual value of the copper plate (the average temperature of eight ordinary thermocouples). The absolute error and relative error of 9# and 10# thin film thermocouple were shown in Figure 11. We can see that the film thermocouple can response the temperature change of the copper plate excellently, and the response time is short. Among them, the maximum absolute error of the needle film thermocouple is 3.67 ℃, and the maximum relative error is 0.47%.

Based on the analysis of experimental results, it is shown that the thin film thermocouple based on MEMS technology has a smaller heat capacity, and shoter response time than the ordinary thermocouple. Furthermore, the maximum absolute error of the thin film thermocouple can be less then ±4 ℃, and its relative error is less than 0.5%. The performance of the thin film thermocouple meets well the design goals.

5 CONCLUSIONS

In this paper, a needle thin film thermocouple for the measurement of high transient temperature on the surfaces of hypersonic vehicle and shuttle vehicle has been researched. The substrate of the thin film thermocouple is made of high temperature resistant ceramic material, and the K-type thermocouple film was deposited on the surface of base top by magnetron sputtering technology. The fabrication process of the thermocouple film lead terminal and thermal junctions were mainly studied and optimized. The performance of the thin film thermocouple was verified by the test system. The test results show that the needle thin film thermocouple owns excellent performance, including short response time, and the relative error of less than 0.5%. It can meet the measurement requirements in the field of transient temperature on surfaces of hypersonic vehicle and shuttle vehicle completely.

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