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STUDY OF AlSiC METAL MATRIX COMPOSITE BASED FLAT THIN HEAT PIPE

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ABSTRACT

AlSiC based flat thin heat pipe prototypes (143.8 x 80.8 x 5 mm^3 outer dimensions) are manufactured. The manufacture process including wick structure design, AlSiC plate processing and plating, soldering the subparts, and finally filling and sealing is presented in this paper. Considering satellite launch conditions, vibration tests involving low/high level sine sweep, medium/low level random and full random are carried out. The temperature profiles over the entire heat pipe are measured by means of infrared (IR) scanning to study the thermal resistance, heat transfer capacity and heat pipe performance degradation, if any. Both horizontal and vertical orientations with different heating-cooling modes are employed in the performance tests. AlSiC based flat thin heat pipes are proven to have excellent performance characteristics. After 42 weeks life test, thermal resistance in the range from 0.15 K/W to 0.5 K/W has been measured at thermal loads from 20 W to 140 W. The lowest thermal resistance is achieved by testing the performance vertically in the top-cooling and bottom-heating mode. Vibration tests cause no degradation of the heat pipe performance.

KEY WORDS: flat thin heat pipe, AlSiC metal matrix composite, AlSiC heat pipe, heat pipe performance, heat transfer capability, thermal resistance

1 INTRODUCTION

Modern communication via satellite links and the related miniaturization of components cause an increasing power density in the microelectronics. The necessary heat removal requires advanced packaging solutions to gain high reliability and long lifetime of the electronic devices. The AlSiC material consists of a continuous aluminium matrix with a multi-modal distribution of SiC particles. It is fully densified and contains up to 80 vol.% SiC. The surface has a several microns thick aluminium skin and can be finished by electroplating. AlSiC metal matrix composite offers advanced properties such as low coefficient of thermal expansion ($6\text{-}8 \cdot 10^{-6}$ K^{-1}), low density (3 g/cm^3) and high thermal conductivity (180-200 W/mK), and attracts a lot of interest in high performance electronic packaging [1]. A new cooling concept combining the use of AlSiC composite and the principle of heat pipes was for the first time proposed a couple of years ago and the advantages of AlSiC heat pipe for thermal packaging applications have been shown [2]. Since electronics is based on printed circuit boards with surface mounted chips, flat thin heat pipes can be more desirable and advantageous for higher power levels [3] and for an uniform temperature along the heat pipe surface [4].

AlSiC based flat thin heat pipes are developed for space applications and advanced performance has been proven [5]. In this paper the manufacture process is presented. Tests and evaluation are also described. The study of AlSiC based flat thin heat pipe includes manufacturing a prototype, testing the prototype and analyzing performance degradation.

2 HEAT PIPE MANUFACTURING

Heat pipe manufacturing includes wick structure design, AlSiC plate processing and plating, joining the subparts, and finally filling and sealing. In this project, soldering two AlSiC base plates is selected to manufacture a flat thin heat pipe. The advantage of such heat pipe is that the whole part is made of

AlSiC composite which leads to a uniform thermal conductivity and, even more important, avoids thermal mismatch stresses between the heat pipe container materials. A technique for soldering large area AlSiC plates must be developed so as to produce a leak-tight seal and to withstand temperatures up to 140°C, as required.

2.1 Wick structure design

Four different manufacturing routes for making AlSiC heat pipes have been considered in the previous projects. As the most useful route, the process involving preparing AlSiC base plates, inserting metal screens to enhance capillary effects and joining the plates is identified in this paper. The outer geometry of the heat pipe (143.8 x 80.8 x 5 mm^3) is selected according to the requirements of potential users. Different versions of heat pipes using grooved, un-grooved AlSiC plates and CuSn screens are studied and prototyped. Fig. 1 shows the AlSiC plate structures.

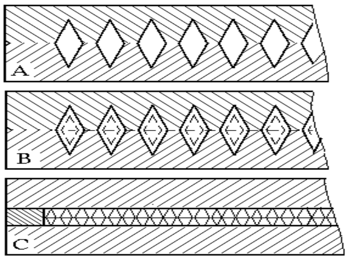

Fig. 1. Schematic diagram of AlSiC plate and wick structure

Version "A" is manufactured by joining two grooved AlSiC plates. Unfortunately, an unexpected low performance of this kind of heat pipe is obtained. In order to enhance the capillary effect, it is necessary to insert screen layers between the two grooved AlSiC plates as shown in version "B". Heat pipe performance is therefore increased. However the advantage of producing version "B" is very low. This is mainly due to the difficulty in manufacturing a fine structured AlSiC plate.

Considering the manufacture process and cost, a flat thin AlSiC plate without grooves as the container plate and a CuSn screen as the wick material are used (see Fig. 1, version "C"). Fig. 2 shows schematically the cross section of the heat pipe version "C". This heat pipe is composed of two AlSiC plates, 5 structured CuSn screen layers, two pins and one frame. For the reason of mechanical stability the screen layers are sintered together before assembling the heat pipe. It enables the screen wick to be fixed inside the cavity during assembling and it guarantees that the screens stay in position over test and lifetime. To fulfill the specified thermal inputs (see section 2.5), 5 layers of screen have been used. CuSn screen fixation is done by means of two NiFe pins soldered onto the AlSiC base plate. This will also prevent the AlSiC plates of distorting and bowing during filling and operation. The coefficient of thermal expansion of the NiFe frame is similar to that of the AlSiC plate. They match each other, leading to low mechanical stresses in the solder layer.

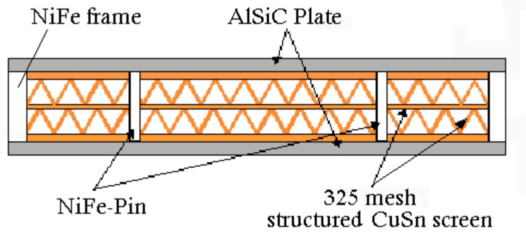

Fig. 2. Schematic cross section of heat pipe.

Fig. 3 shows the subparts used for the prototype manufacture including AlSiC base plates, frame with filling tube and CuSn screen. High production yield and cost-effective manufacture procedure have been achieved. The high thermal performance of heat pipe version "C" will be presented in section 3.

Fig. 3. Subparts of flat thin heat pipe
(1, 4: Ni/Au plated AlSiC plates; 2: NiFe frame; 3: CuSn screen; 5: heat pipe)

2.2 Treatment and finishing of AlSiC plate

The AlSiC plate used is produced by an infiltration process developed at Electrovac. It is ground from both sides to a flat thin shape and to a nominal thickness, for example, 1mm for manufacturing the prototype. After grinding, the AlSiC plate is used for a further surface treatment. On the other hand, grinding removes the aluminium skin which is around the infiltrated SiC particles. It has been indicated that the missing aluminium might result in problems during surface treatment. The surface of the ground planar AlSiC plate must be well treated before Ni plating.

Finishing the AlSiC plate deals with plating Ni, and afterwards Au on it. The SiC particles may get picked off during grinding and they get loosened by ultrasonic cleaning. Ni can be easily deposited on an aluminium surface, but in the case of AlSiC, the surface has to be activated in order to obtain good adherence between Ni and SiC particles. A pre-treatment procedure for surface activation prior to Nickel deposition is necessary to solve the Ni adhesion problem. After pre-treatment, electroless nickel plus a thin gold layer is firstly tried.

To test the quality of the plating, an annealing process is introduced. A bad adherence has been observed. It is assumed that cracks are initiated and the Ni layer delaminates from the AlSiC plate. It has been found that the annealing conditions (time, temperature, atmosphere) exert an influence on the hardness of the Ni plating. When it is annealed at high temperature, for example at 350°C and for a long time, 30 min, the hardness increases rapidly. The hardness increase is due to transformation of the amorphous into the crystalline state. Further trials are made to treat the AlSiC plate. After electroless Ni plating (Ni thickness 8-10 µm), an electrolytic nickel layer (9 to 11 µm thick) is applied. Afterward, Au is plated on the Ni layer. Any blister and crack on the thin Ni/Au layer may cause the vapour of the working fluid (water) to get into contact with the AlSiC material to lead to corrosion of the base plate and to generation of non-condensable gas during heat pipe operation.

2.3 Soldering process

Any mechanical and thermal stresses in the solder area cannot be removed by plastic deformation. They will lead to cracks and rupture of the joint. To avoid stresses due to thermal mismatch, the frame shown in the Fig. 3 should have a similar thermal expansion coefficient as the plates. Nickel Iron frame (NiFe, 46 % Ni, Fe rest) is chosen, as it fits the thermal expansion of AlSiC, but there are still some deviations on the expansion curves which are reason for stresses in the joint.

Different solders and solder techniques are investigated in order to get a He leak-tight seal. Standard type solders such as PbSn, SnAg, PbSnAg or PbInAg are used in solder preform or solder cream. No He leak-tight soldering could be realized. This is mainly due to the fact of the large joining area, the properties of solders used and due to the blisters and cracks which occurred on Ni/Au thin layer. AuSn is also a standard solder used in the electronic industry. The working point of AuSn is approx. 300°C. It forms a eutectic composition with eutectic melting point 280°C. Au80Sn20 is selected to join the heat pipe subparts. The first batch of prototypes could be soldered without problems in a continuous belt furnace, but the results were not reproducible in the next batch although the same materials and same procedures were involved. It has been found that the leak-tightness of heat pipe depends strongly the on soldering process and Ni/Au layer on AlSiC.

The thickness of the solder preform can be reduced by using AuSn solder, for example, from 0.4 mm in the case of SnAg to 0.05 mm for AuSn. After optimizing the Ni/Au plating process and soldering process, leak-tight AlSiC flat thin heat pipe prototypes are successfully manufactured. The heat pipe subparts are joined by heating them up to about 320°C in nitrogen/hydrogen atmosphere using AuSn solder preform. This temperature is slightly higher than the peak temperature of the soldering process.

2.4 Working fluid and charge optimization

For the prototype presented in this paper, water is chosen as the working fluid. Two charging procedures can be used to fill the heat pipe with working fluid. In procedure one, the heat pipe is completely evacuated firstly, then filled with a specified amount of degassed working fluid. In procedure two, the evacuated heat pipe is completely filled with degassed working fluid and then a specified amount of fluid is driven out by heating the heat pipe at the evaporator area. The second technique is as accurate as the first one but takes more time. The heat pipe is sealed by a plug in the same way as in procedure one.

An input power of 150 W is added to the AlSiC heat pipe and the adiabatic temperature is maintained at 60°C. Under these conditions, water is gradually evaporated. A relationship between water amount and thermal resistance is generated to optimize the fill charge. The optimum fill charge is determined between 10.4 g to 9 g, in which the performance remains practically constant. The heat pipe prototypes are filled with fill charges in this range. The overall thermal resistance is related to the temperature difference between heating area and cooling area and the applied thermal load. The „plug“ sealing technique for the filling tube has been demonstrated as a very reliable method.

2.5 AlSiC heat pipe prototype

The prototypes of AlSiC flat thin heat pipe are manufactured as shown in Fig. 4. Water is filled as the working fluid. The prototype has a dimension of 143.8 mm in length, 80.8 mm in width and 5 mm in thickness.

Fig. 4: AlSiC heat pipe prototypes

The heat pipe leak rate should be less than 10^{-9} mbarl/s. Non-condensable gas (NCG) generation length is required to be less than 3% of the heat pipe length. These prototypes are used for performance study, life tests and vibration tests as described below. The requirements for temperature range in operation and non-operation mode, the thermal cycles and burst pressure will be described somewhere else. Heat transport capability of the heat pipe prototype should be higher than 100 W. The maximum heat flux shall be demonstrated up to 10 W/cm^2 at the evaporator and condenser area. The heat pipe should meet the vibration requirements without degradation. The heat pipe is required to meet the specification throughout a nominal 15 years lifetime in space after 5 years of ground storage and testing. The following heat pipe test will show the characteristics of the AlSiC based flat thin heat pipe.

3 TESTS OF HEAT PIPE

3.1 Thermal performance tests

Performance test shows whether the prototype exhibits characteristic of heat pipe and whether it is an ideal heat pipe for transporting the dissipated power. Any degradation with life test and after vibration test can also be determined by performance tests. A performance comparison with an unfilled heat pipe is also done. The prototype is mounted on a rotary test rig so that performance can be tested horizontally, vertically and at any inclination. The angle of the heat pipe can be set accurately. Fig. 5 shows schematically a vertical test set-up. A ‘Varioscan’ high resolution scanner is used instead of thermocouples to measure the temperature. This IR scanner has many advantages. One of them is to measure temperature and temperature profiles over the entire heat pipe. The test parameters are given as follows:

- Heating area: 9.5 cm2 (2.5 x 3.8 cm^2)
- Thermal load: 20-160 W
- Cooling medium: water
- Cooling area: 40 cm^2 (2.5 x 8 cm^2 for each side)

During performance test, the heat pipe can be heated from either the front side or back side, and it can also be cooled from either the front side, back side or both sides with different cooling areas. A large heater and small cooling area are also used to study the heat pipe performance (heating area: 40 cm^2, cooling area: 9.2 cm^2). Results of these tests are not reported in this paper.

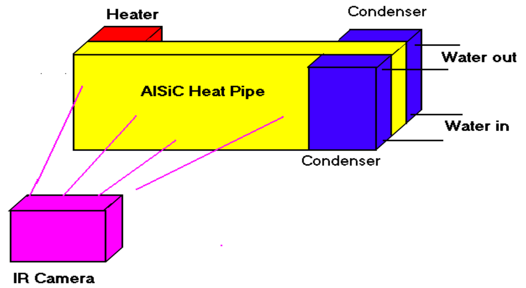

Fig. 5. Vertical set-up for performance test

The temperature profile over the entire heat pipe is recorded by means of IR scanning. The following information can be obtained from IR images:

- adiabatic area and temperature
- temperature profile over the heat pipe
- temperature change with input power
- thermal resistance change with input power
- performance loss, if any
- local/entire defect of heat pipe, if any
- thermal resistance change with time

3.2 Vibration tests

Withstanding typical launch conditions requires mechanical strength of joints and interfaces at a certain level. Vibration testing and performance check afterwards shall give a first hint for withstanding launch conditions. The vibration test is carried out using Electrodynamic Vibration Exciter System LDS V864 HT-440. The heat pipe should be hard-mounted over the complete surface, i.e. the test should investigate any change of the inside structure of the heat pipe. The following sequence is applied to each heat pipe axis separately. The heat pipe should meet these vibration requirements without performance degradation. The test specifications are given as follows:

- Low level sine sweep with 0.5g from 5Hz to 2000Hz (2 oct/min)
- High level sine with 25g from 5Hz to 100Hz (2 oct/min)
- Medium/low level random 0.2 g2/Hz for 2 min
- Full random 0.7 g2/Hz for 2 min
- Low level sine 0.5g from 5Hz to2000Hz (2 oct/min)

4 RESULTS AND DISCUSSION

4.1 Thermal Performance

Fig. 6 shows typical IR images of the surface of a filled (left) and an empty heat pipe (right) using the horizontal set-up. In this case the heater is located on the other side of heat pipe, while condensers are located on both sides. The empty plate shows the typical near linear temperature drop of a solid plate (here AlSiC composite), whereas in the filled heat pipe a relatively large adiabatic section is formed, demonstrating the heat pipe action. The two-dimensional temperature field is due to the heat losses along the side of the plate.

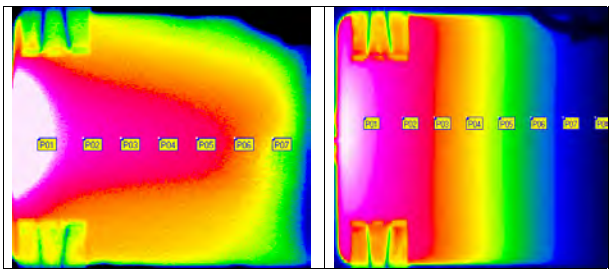

Fig. 6. IR images of filled (left) and empty heat pipe (right) at 100 W using horizontal set-up

Fig. 7 gives the temperature profiles along the central axis of the heat pipe at thermal load of 60 W. A low adiabatic temperature, 21.9°C, is achieved along the axial position, indicating an excellent heat pipe performance. For the empty heat pipe, the surface temperature increases linearly from the cooling area to the heating area.

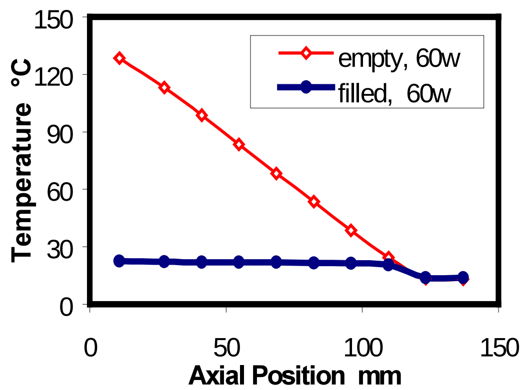

Fig. 7. Temperature profiles of empty and filled heat pipe

Fig. 8 gives the temperature profiles on both heat pipe sides at a thermal load 140 W. It is interesting to notice that the temperature profiles are same on both sides except for the heating area. It is found that the highest temperature of the heating area is 124.3°C, while that of the opposite area is only 36.1°C. Heat transfer is so effective that a high temperature gradient is built up across the plate thickness within just 5 mm. In other words, a cold surface can be formed on one side even though the opposite side is heated to 124.3°C. This characteristic of AlSiC heat pipe plate may find special applications in the electronics industry.

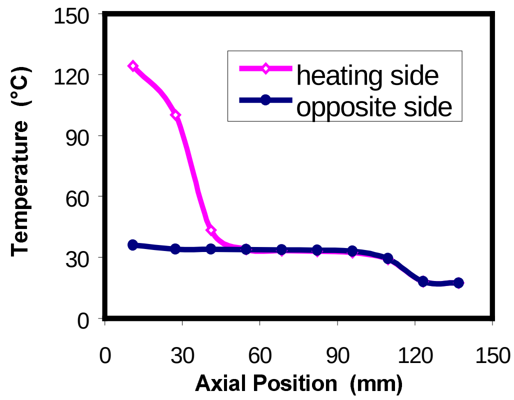

Fig. 8. Temperature profiles on both sides of the heat pipe (140 W)

The effective thermal conductivity of heat pipe can be calculated as:

$k = L*Q/A*\Delta T$

where,

k : effective thermal conductivity

L: length of heat pipe,

A: area of cross section

ΔT: temperature difference between the evaporator and condenser ($T_e - T_c$)

Fig. 9 shows the thermal conductivity of the heat pipe. The conductivity of the empty heat pipe is calculated to be 175-184 W/mK, while the thermal conductivities of the filled heat pipe are calculated to be 1522-4336 W/mK for vertical performance (top-cooling and bottom heating) and 1429-3245 W/mK for horizontal test.

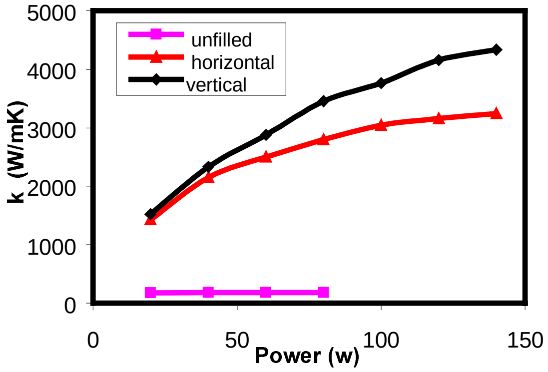

Fig. 9. Thermal conductivity of heat pipe

4.2 Performance before and after vibration

Fig. 10 shows the temperature profiles taken after 42 weeks of life testing. There is practically no difference to the performance at the start of the life testing. So a long-term degradation can be excluded. After the long-term test the respective heat pipe was subjected to vibration tests. Fig. 11. shows the performance of this heat pipe after the vibration tests. Practically no obvious difference in temperature profiles can be seen. This means that no mechanical damage occurred during the vibration tests and there is no performance degradation.

Fig. 12 shows the thermal resistance of the heat pipe before and after vibration tests. It is calculated as follows:

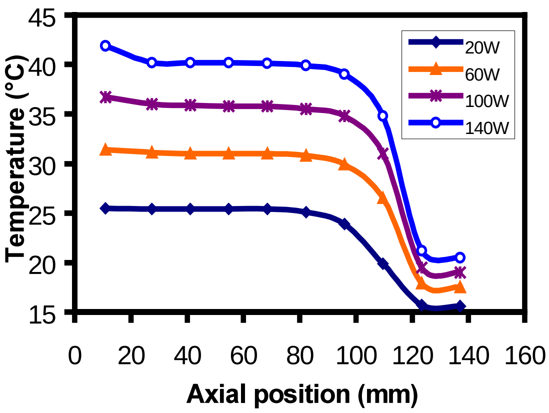

Fig. 10. Performance after 42 weeks life test

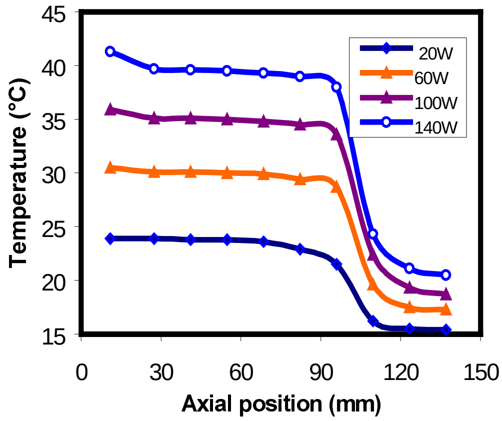

Fig. 11. Performance after vibration test

$R_{th}=(T_e - T_c)/Q$
where,
T_e: evaporator temperature
T_c: condenser temperature
Q: heat input (thermal load)

The thermal resistance remains the same as that measured before the vibration tests. It is clear that the heat pipe performs well and there is not any performance loss after the vibration tests.

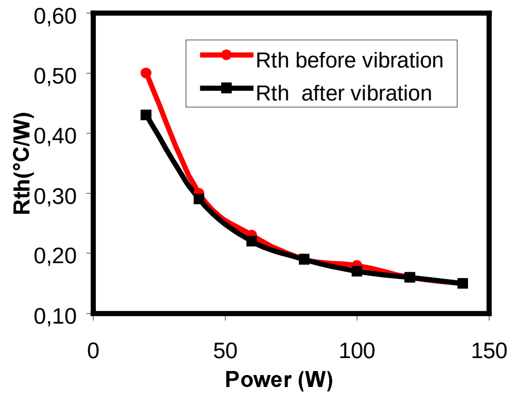

Fig. 12. Thermal resistance before and after the vibration tests

4.3 Problems encountered during AlSiC heat pipe production

Possible problems during AlSiC heat pipe production can arise from:

- AlSiC raw plate production
- Grinding the raw plate to a flat thin shape
- Surface treatment and finishing of the thin plate
- Soldering process

The problems arisen from the AlSiC raw plate production had been solved in a previous project. A reliable AlSiC plate is available. Solving the problems related to grinding the raw plate, surface treatment and finishing of the flat thin plate and the problems appearing during the soldering process are the most important tasks in the present project. As mentioned above, leakage is the major reason for heat pipe failure. This failure is strongly related to the cracks and blisters of the Ni/Au layers and their adhesion to the AlSiC plate. The mismatch of thermal expansion and related stresses are analyzed. The soldering process is optimized by selecting the solder and soldering parameters. After a lot of trials, the leakage problem has been solved. Before Au is plated on the electroless Ni layer, a nickel 'strike' layer is applied. This is a very thin nickel layer (9-11 µm). During its deposition strong hydrogen generation happens, which results in a cleaning effect and removing existing surface oxides. This nickel strike layer acts like a buffer layer and prevents the electroless Ni layer from cracking during the soldering process. The overall manufacturing yield is significantly increased.

5 CONCLUSIONS

By using CuSn screen layers instead of simple grooved AlSiC as the wick material, the capillary effect of the heat pipe is greatly enhanced. The heat pipe manufacture process is simplified and the production cost can be dramatically decreased by soldering two flat thin AlSiC plates and inserting the screen wick in between. The treatment and plating process of the AlSiC plates determine to a great extent the helium leak-tightness of the heat pipe. Cracks and blisters appearing on the surface layers are prevented by applying a buffer layer, e.g. an electrolytic Ni layer between the electroless Ni layer and Au layer.

The optimum water charge lies in the range of 9 and 10.4 gram for the heat pipe with dimensions 143.8 x 80.8 x 5 mm^3. An excellent performance of the AlSiC heat pipe is achieved. Thermal resistances in the range from 0.15 K/W to 0.5 K/W are measured at applied thermal loads from 20 W to 140 W after 42 weeks of life testing. The vibration tests cause no obvious degradation of the heat pipe performance. The adiabatic temperature and area are same as before the vibration test. The same thermal resistance is also measured before and after vibration tests, showing the mechanical resistance (leak-tightness) and wick structure stability. The manufacturing process of AlSiC based flat thin heat pipes has been successfully developed.

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