Appl. Math. Mech. -Engl. Ed., 2008, 29(1):51-60
DOI 10.1007/s10483-008-0107-1


**Applied Mathematics and Mechanics (English Edition)**

# Research progress on thermal protection materials and structures of hypersonic vehicles *

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(Communicated by MENG Qing-guo)

**Abstract** Hypersonic vehicles represent future trends of military equipments and play an important role in future war. Thermal protection materials and structures, which relate to the safety of hypersonic vehicles, are one of the most key techniques in design and manufacture of hypersonic vehicles. Among these materials and structures, such as metallic temperature protection structure, the temperature ceramics and carbon/carbon composites are usually adopted in design. The recent progresses of research and application of ultra-high temperature materials in preparation, oxidation resistance, mechanical and physical characterization are summarized.



**Key words** hypersonic vehicle, high-temperature, thermal protection

**Chinese Library Classification** V250.1
**2000 Mathematics Subject Classification** 76K05

## Introduction

Hypersonic aircrafts, such as ballistic missiles, homing missiles, cruise missiles, reentry vehicles, trans-atmospheric vehicles and hypersonic airplanes, are a group of space vehicles, whose flight speed exceeds 5 Mach. Characterized by high maneuverability, long-distance and accurate destroy ability, hypersonic weapons have become the developmental direction of military equipments and will play an important role in the future war. Comparing with traditional weapons, hypersonic vehicles have many advantages, such as less response time, high ability of penetration, anti-defense and better viability of weapons[1]. Many countries, such as America, Russia, France, Germany, Japan and India, are devoted to improve hypersonic technology. Recently, many plans, such as Affordable Rapid Response Missile Demonstrator (ARRMD) plan made by Defense Advanced Research Projects Agency of America (DARPPA), HyTech plan by United States Air Force, Cool plan made by Russia, Prometheus plan made by France and ShyFE plan made by UK, have been made to encourage the research in this area. Supported by these plans, a lot of hypersonic aircrafts have been completed, such as AIM54C Phoenix missile (5 Ma), Fasthawk cruise missile (5 Ma). Now, new higher speed hypersonic aircrafts, whose flight speed exceeds 10 Mach, are being studied in some countries. With higher and higher

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flight speed, aircrafts' service environment is becoming worse and worse. Thermal protection system is playing more and more important role in aircrafts' safety. Thus, research of thermal protection structures and materials of hypersonic vehicles has been becoming more and more important.

## 1 Large scale thermal protection materials

Large scale thermal protection materials are used in aircrafts except the highest temperature areas. Ceramic tiles are traditionally used as large scale thermal protection materials. However, their brittleness, low damage resistance and high maintaining cost prevent the further application of these materials. Metallic thermal protection structures (TPS) is the main developmental direction of modern thermal protection systems.

### 1.1 Structure design of TPS

NASA Langley Research Center began to study metallic TPS supported by United X-20 plan[2] in the 1970s. From then on, metallic TPS configurations have been improved from early stand-off structure, multiwall structure, super alloy with honeycomb sandwich to ARMOR structure[3−6].

(1) Stand-off structure

The outer surface is comprised of wave metal panels and the inner core uses different configurations (shown as in Fig. 1), such as wave, strip, honeycomb and lattice structure. The thermal protection panel is fixed by fasteners at the outer surface edge. Insulations are placed in the space between the outer thermal protection panel and the inner structure. However, this thermal protection configuration has no moisturepro of function.



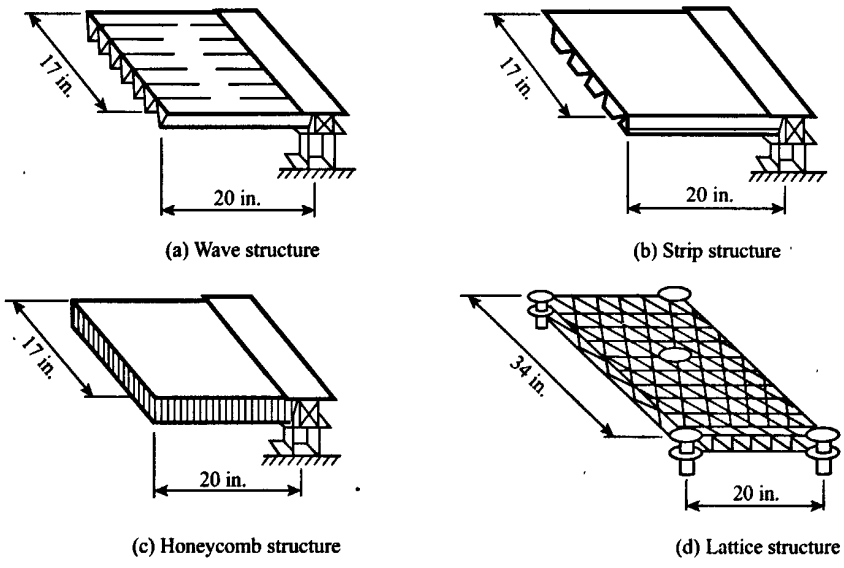


**Fig. 1** Stand-off structure of TPS

(2) Multiwall structure of TPS

Multiwall structure of TPS consists of metal sheets and a honeycomb core. The metal sheets and a honeycomb core, which are made of titanium and nickel alloys, are connected through a special welding process (shown as Fig. 2). Compared with stand-off structure, titanium multiwall structure possesses better heat endurance. However, it has larger density and lower efficiency, especially at high temperatures. Hence, the inner titanium multiwall structure is replaced by the lightweight fibrous insulation.

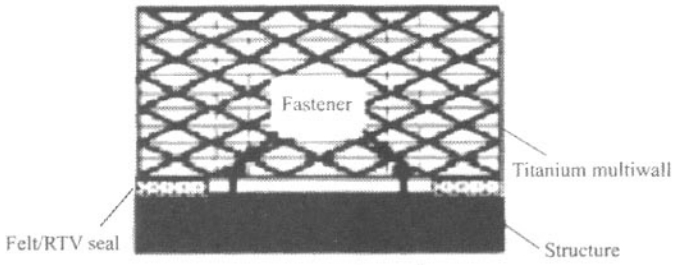


**Fig. 2** Multiwall structure of TPS

(3) Super alloy with honeycomb sandwich

Super alloy with honeycomb sandwich consists of Cerrachrome and Q-fiber insulation, which forms higher and lower temperature insulation. The outer surface is comprised of a foil-gage Inconel 617 honeycomb sandwich and the inner surface is a titanium honeycomb sandwich with a part of one facesheet and the core removed to save weight (shown as Fig. 3). The improved honeycomb sandwich TPS uses lightweight fibrous insulation (Saffil insulation) and foil to further decrease its mass.



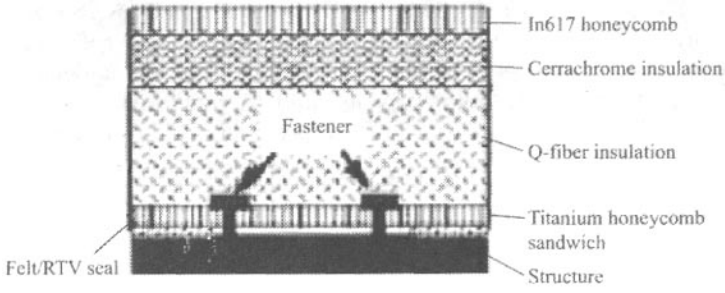


**Fig. 3** Super alloy with honeycomb sandwich structure

(4) ARMOR thermal protection structures

ARMOR TPS is one of the important candidates for thermal protection systems. Each square panel is mechanically attached to a metallic, stand-off bracket at each corner, and stand-off bracket is made of Inconel 718. The novel stand-off bracket provides a way to release load between the outer hotter surface and the inner colder surface. It does not only avoid heat short, but also allows free thermal expansion for the outer surface. It is convenient to increase the thickness of Inconel 617 honeycomb sandwich panel in order to meet the ARMOR TPS strength request.

### 1.2 Testing and Characterization of TPS

Many researchers have finished experimental and theoretical studies about large scale thermal protection materials in the past years. Cunnington[7] measured the effective thermal conduction coefficients of seven multi-layer insulation structures and set up a theoretical model. Keller[8] studied the radiative heat transfer of multi-layer insulation structures by ignoring thermal conductivity of solids. Applying approximate heat flux method, Daryabeigi[9−13] presented some computational models for analyzing the radiative heat transfer of multi-layer insulation structures. In order to solve the key issues of aircrafts, metal TPS with two functions (thermal protection and supporting mechanical loads) was performed by States Air Force of America. A

series of experimental tests and analytical methods[14–23] are being developed to characterize and improve metallic TPS. The tests included rain erosion tests, low-speed and hypervelocity impact tests, thermal vacuum TPS panel tests, arcjet TPS panel tests and acoustic TPS panel tests. Rain erosion flight tests on an F-15 aircraft were conducted by Rockwell International at NASA Dryden. A special fixture was designed to suspend TPS samples beneath an F-15 aircraft. The fixture provided eight rows of TPS samples. Each row had a sample at 0°, 10° and 20° angle of attack. Therefore, eight TPS concepts could be tested at three different angles of attack, respectively. The primary purpose of the tests was to evaluate the rain erosion resistance of rigid ceramic tiles and flexible blankets. However, preoxidized Inconel 617 and titanium honeycomb sandwich samples were also tested. The metallic specimens were tested at a variety of conditions from light mist to very heavy rain at speeds up to 500 knots over the course of five test flights. Low-speed impact tests were performed on a variety of Inconel 617 and titanium honeycomb sandwich specimens using the low-speed impact facility at NASA LaRC (Figure 5). The facility features a dropped impactor which is used to measure the impact force profile. Interchangeable impact heads provide variable impact radii. A knife-edge support fixture can be simplified as supported boundary conditions for the 10-cm-square impact specimens. More than 30 metallic TPS specimens were tested at the light gas gun facility at NASA Marshall Space Flight Center (MSFC).

A special fixture was developed to hold honeycomb sandwich coupons, internal insulation, a coupon of titanium foil or honeycomb, and substructure panel to simulate a TPS panel attached to a substructure. Aluminum spheres from 0.125 to 0.25 diameters were fired at the specimens at 7 km/sec. The four panel array was tested in the arcjet at NASA Ames. The four TPS panels were mounted to a representative composite fluted core structural panel using bonded threaded studs. Thermocouples were located at several locations under the sides of the panels in the gaps and on the substructure. An infrared thermal camera was used to observe the temperature distribution on the surface of the array. In addition, several analytical models were constructed to predict the thermal and structural behavior of superalloy honeycomb TPS. Detailed three-dimensional finite element and finite difference models were developed for the TPS panels. One-dimensional finite element heat transfer models were developed to predict complex thermal performance of fibrous and multilayer insulations as a function of temperature and pressure. A one dimensional TPS sizing code has been developed and enhanced to predict the thickness and the mass of a TPS required for a particular location on a vehicle.



## 2 Ultrahigh temperature thermal protection materials

Ultrahigh temperature thermal protection materials are used in the highest temperature areas of hypersonic aircrafts, such as cone and wing edges. Ultrahigh temperature thermal protection materials include refractory metals, ceramic composites, modified C/C composites, etc. Due to high cost, hard machining, low oxidation resistance and large density, refractory metal is hard to be a candidate of thermal protection material for hypersonic vehicles. Ceramic composites and modified C/C composites are the developmental trend of ultrahigh temperature thermal protection materials.

### 2.1 C/C composites

C/C composites are the combination of carbon rein with carbon fiber. Having excellent mechanical properties, such as high specific strength, high specific stiffness, small thermal expansion coefficient, good corrosion and heat shock resistance ability, C/C composites are becoming an important ultrahigh temperature thermal protection material. There have been great improvements for C/C composites in aviation and spaceflight field since 1958. C/C composites are mainly used to make warhead components, aircraft thermal protection components and aero-engine hot end components[24,25]. Although C/C composites have many advantages, it can not be used at high temperatures due to its oxidation above 500°C without any coating.

The research work about C/C composites is focused on how to promote oxidation resistance property and how to control coating failure. Walker[26] presented the oxidation mechanism. There are two ways to promote oxidation resistance property of C/C composites. One is by enhancing its own oxidation resistance, and while the other is by using oxidation coating. Matrix dipping and inhibitor can enhance its own oxidation resistance of C/C composites. Some borides, such as $B_2O_3$, $B_4C$ and $ZrB_2$, are often used as inhibitors[27−32]. In recent years, oxidation-resistance coating techniques of C/C composites have been improved greatly. Some new preparation methods[33−43] of coatings, such as one-component coating, multi-component coating, composite coating, composite graded coating and precious metal coating have been put forward. The preparation methods of coating include CVD method, PACVD method, sol-gel method and liquid-phase method, etc. Heat stress occurs at the interface of coating and C/C composites for thermophysical properties' difference. This leads crack extend and fall from coating. How to optimize coating structure to avoid the mismatch of matrix and C/C composites is a key point[44]. Until now, there is still no C/C composites, which can be used in air above 2000°C for long time.

## 2.2 Ultrahigh temperature Ceramics

Among the ultrahigh temperature ceramics (UHTCs) are a group of materials consisting of transition-metal compounds with high melting point, such as $ZrB_2$, TaC, HfN, $HfB_2$, ZrC, etc. UHTCs have good chemical and physical stability at ultra-temperature conditions. The studies on UHTCs are focused on the oxidation behavior as well asstrengthening and toughening mechanisms. UHTCs were initially presented in the 1950s[45]. Compositions with 5 to 50 vol.% SiC were investigated for both $ZrB_2$ and $HfB_2$ over a wide range of test temperatures and pressures. 20 vol.% compositions were judged optimal for hypersonic vehicles after a series of efforts[46−50] supported by the US Air Force. Additions of C improved thermal stress resistance, but were detrimental to oxidation resistance at all proportions. Shaffer[51] evaluated the oxidation resistance of $ZrB_2$ with additions of the disilicides of Ta, Nb,W, Mo, Zr, $Mo_{0.5}Ta_{0.5}$, and $Mo_{0.8}Ta_{0.2}$, as well as $Zr_5Si_3$. Pastor and Meyer[52] evaluated the oxidation resistance of $ZrB_2$ with additions of $MSi_2$ or $M_5Si_3$, where M is a transition metal Zr, Ta, Cr, Mo, or W. On the basis of scale thickness measurements after oxidation testing for up to 100 h at 1200 and 1400°C, the $ZrB_2$+15wt.%$CrSi_2$ composition was found to be the most oxidation resistant. Lavrenko and coworkers[53−55] reported that a $ZrB_2$+50wt.%$ZrSi_2$ composition was more oxidation resistant than $MoSi_2$ and $WSi_2$, and could be used up to 1700°C. Kuriakose and Margrave[56,57] measured weight changes for $ZrB_2$ over the temperature range of 945-1256°C and also reported parabolic oxidation kinetics. In addition to the diborides, other materials were investigated for potential hypersonic applications[58−61]. Materials based on ZrC and HfC were extensively studied, but were found to oxidize (nonprotectively) below 1800°C, which eliminated them from consideration for the temperature cycling hypersonic applications. In the 1970s, many researches began to realize that $ZrB_2$ and $HfB_2$ compounds would become the best thermal protection materials which can withstand temperatures up to 2700°C[62]. In order to keep sharp cone and front wing edges in hypersonic aircraft flight, SHARP plan was performed. NASA Sandia developed $ZrB_2$ and $HfB_2$ compounds UHTCs, whose density is 98%. NASA Ames Research Center compared the ablation resistance property of C/C composites with that of $ZrB_2$ ceramic. The result showed that the ablation mass of C/C composites is 130 times larger than that of UHTCs in the same condition. NASA Lewis Research Center studied the oxidation and ablation behaviors of UHTCs in extreme condition. $ZrB_2$ ceramic exhibited good oxidation resistance and thermal shock resistance properties in arc heated tunnel ablation tests. Only much thinner oxide formed when $ZrB_2$ ceramic samples were oxidized at 1800°C for 300 seconds. Stanley[63] examined three of UHTCs more representative of a propulsion environment, i.e., higher oxygen partial pressure and total pressure. Results of strength and fracture toughness measurements, furnace oxidation, and high velocity thermal shock exposures are presented for $ZrB_2$ plus 20 vol.% SiC, $ZrB_2$ plus 14 vol.% SiC plus 30 vol.% C, and SCS-9a

SiC fiber reinforced $ZrB_2$ plus 20 vol.% SiC. Monteverde[64] investigated the resistance to oxidation in ambient air at a temperature up to 1600°C of two hot-pressed diborides matrix composites, both containing 19.5 vol. % SiC and 3 vol. % HfN. The result showed that modest weight gains and limited corrosion depths highlighted a rather good thermal stability. Monteverde[65] successfully produced ultrahigh temperature $HfB_2$-SiC ceramics by reactive hot-pressing (RHP) and spark plasma sintering (SPS). The material processed by SPS retained its original strength and fracture toughness up to 1500°C.

Another kind of UHTCs is C/SiC composites, which possess many advantages, such as low density, high strength, high temperature endurance, good ablation and impact resistance. The oxidation resistance property of C/SiC composites are better than that of C/C composites. Oak Ridge Lab(America), SEP Co. (France) and Karslure University(German) began research works on C/SiC composites in the 1980s. C/SiC composites were used in the thermal protection structures of Hermes airship, Hotel and Sanger space shuttles. A novel C/SiC ceramic, which could work in oxidation atmosphere at 1650°C, was developed by North western Polytechnical University. The bending strength at room temperature was above 700MPa and the fracture toughness was 19~20 MPa · $m^{1/2}$. The preparation methods of C/SiC composites include RMI method, LPI method and CVI method. Bertrand[66] developed two generations of multilayered interphases, composed of carbon and silicon carbide, which act as a mechanical fuse in SiC/SiC composites with improved oxidation resistance. Examinations were then performed on the loaded samples and damaging mode characterized at nanometric scale. Macroscopic results for a 2.5D $C_f$-SiC composite creep tested in tension are presented by Boitier[67,68]. Dalmaz[69,70] studied the characterisation of the elastic properties of a long-fibre-reinforced ceramic-matrix composite. Seven of the nine independent elastic constants of a woven 2.5D carbon-fibre reinforced SiC ceramic matrix have been measured by an ultrasonic technique associated with a numerical optimisation process. Halbig[71,72] investigated oxidation behaviors of C/SiC composites under a static tension load. Kiyoshis[73−75] studied self-healing and roughness-enhancing of C/SiC composites. Many research works[76,77] were performed by North Western Polytechnical University



## 3 Conclusions

Thermal protection structures and materials of hypersonic vehicles is one of the key technologies in aircrafts' design and manufacture. It is a challenge task to develop thermal protection structures and materials for hypersonic vehicles because of the hostile service environment. A lot of notable progresses on manufacture methods, oxidation resistance methods, service environmental simulation, mechanical and physical properties' characterization of thermal protection materials have been made by ceaseless efforts. However, the existing thermal protection materials can not meet the requirements of new hypersonic vehicles with higher and higher speed. Especially, the thermal protection materials used in high temperature air condition for a long time should be deeply studied. The authors think some key research issues should be emphasized as follows:

(1) Air thermodynamic models and simulation methods;

(2) Test methods of thermal protection materials in aircraft service condition;

(3) Oxidation mechanism and micro-structure design of UHTCs;

(4) Methods of strengthening, toughening and thermal shock resistance of UHTCs;

(5) Integrative design of anti-oxidation/load-carrying/anti-thermo-cracking for thermal protection of structures and materials.

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