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High-power laser resistance of filled sandwich panel with truss core: an experimental study

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Abstract We reported a new function of sandwich panels with truss cores, i.e., superior performance under intense local heat flux induced by continuous wave laser. To further enhance the laser resistance, lightweight ablative material and thermal insulation material are filled in the sandwich panel respectively. A dimensional analysis is developed to find core filler materials with appropriate properties. Experiments show that sandwich panels filled with the compound of silicone resin and carbon powder, a typical ablative material, and porous ceramic, a typical thermal insulation material significantly improve the local heat flux resistance compared with monolithic plates and unfilled sandwich panels. The full-field temperature history and dynamic damage evolution of the back surface are recorded and compared, and the failure time to reach the melting point is prolonged in the following order: monolithic plate, unfilled sandwich panel, sandwich panel filled with ceramic, sandwich panel filled with the compound of silicone resin and carbon powder. Considering the lightweight design requirement of such structures, resistance in relation to specific weight is also evaluated and discussed.

Keywords laser resistance, sandwich panel, thermal insulation, lightweight structure, failure point

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1. Introduction

High-power laser-matter interactions have received increased attention in various conditions, including laser welding [1, 2], laser drilling [3], laser cutting [4] and laser processing [5], as well as in the study of laser induced damages. When exposed to a high-power continuous wave (CW) laser, one of the most practical interests for structures used in the aerospace industry is the time that the melt front reaches the opposite surface. Inner equipment may be considerably harmed or damaged when the outer skin is burned through. Specific shields should be designed and installed to improve resistance to such intense heat flux.

Some integrated thermal protection systems (ITPS) with lightweight and thermal insulation properties are designed with sandwich structures for aerodynamic heating during the launch and re-entry flight [6, 7]. Among those, newly developed sandwich panels with truss cores (SPTC) theoretically and experimentally showed superior specific mass performance under static and dynamic loading [8-12]. In addition, an open-cell truss core provides easy access to other lightweight materials to be filled in order to further improve the performance of the SPTC. Responses of metallic sandwich panels filled with either polymer or metallic foams have been investigated because of low manufacturing cost. The foam filled in the core can dramatically increase the specific compression strength [13], shear strength [14], specific energy absorption ability [13], perforation resistance [15, 16] and the blast resistivity [17] of sandwich panels. Recently, Karttunen et al. [18] found that the foam filled sandwich panel also

demonstrates a better fatigue strength performance. However, up to now no experimental data are reported on the high-power laser resistance of SPTCs or filled SPTCs.

A number of different failure modes exist when a structure is subjected to high-power laser irradiation. The failure mode is dependent on laser powers, material properties, structural features and environmental parameters. The thermal deformation induced by the thermal stress through non-uniform temperature distribution is the main failure mode of structures under low-power CW laser irradiation [19]. The laser also reduces the stiffness and strength of a target when temperature is below the melting point of a material [20]. With increasing laser powers, the surface temperature shortly rises to the melting point, and the primary damage mechanism is the material removal caused by evaporation and melts expulsion from the center of the laser spot [21]. High-speed airflow may also strongly affect the mode and threshold of the laser damage. Tangential airflow increases ablative rate by removing melted materials and reducing burn through time [22-26]. This airflow also eliminates the oxide produced by the oxidation of material and supplies extra oxygen. In addition, airflow causes pressure difference between two surfaces of thin-plate targets, leading to a premature rupture at the temperature well below the melting point [27]. Numerical analyses are also performed to examine the laser damage of composite materials in supersonic airflow [28].

Most aforementioned works have focused on affecting factors and failure

mechanisms of laser irradiated materials. Few studies have investigated on strategies for improving the laser resistance of structures with less weight. In this paper, we reported an effective way to reduce the laser damage by using the SPTC. By filling the void space of the truss core with light-weight materials of appropriate properties, an integrated design for thermal insulation/load bearing/laser resistance can be obtained. Firstly, the mechanism of higher laser resistance of the SPTC and the filled SPTC is introduced. Then, a dimensional analysis is performed to find the appropriate material to be filled in the truss core. A series of experiments were conducted to obtain the laser resistance of the unfilled SPTC, filled SPTC and monolithic plates with equal areal densities. Experimental results show that filled SPTCs demonstrate improved laser resistance compared to monolithic plates. The SPTC filled with the compound of silicone and carbon powder is found to have the highest laser resistance.

2. Conceptual analysis of the laser resistance of SPTC

Recently, we found that SPTCs have a better performance on laser resistance compared to monolithic plates with approximately equal areal densities. Fig.1 shows experimental results of the SPTC irradiated by 2000 W laser with a spot diameter of 30 mm for 30 s. The melting front reached the inside surface of monolithic plates, i.e., it is burn through. In contrast, although the laser irradiated facesheet is seriously damaged, the damage in the opposite facesheet or the inside surface of the SPTC is negligible. This performance is especially beneficial for a space structure or a thermal protection structure during service: the structure may still possess certain strength and maintain

structural integrity. Our previous study indicates that the residual strength of the SPTC is insensitive to local damages of holes in one of the facesheet [29].

The mechanism of superior CW laser resistance for the metallic SPTC can be illustrated in Fig.2. Intense input heat is dissipated or transferred mainly in three ways: (1) the in-plane heat conduction in the outside facesheet or laser irradiated facesheet; (2) heat conduction along truss members and (3) radiation from outside facesheet to inside facesheet. The last two items determine the amount of heat transferred to the inside surface. Owing to the low relative density of the truss core, heat conduction to the inside surface along truss members is comparable to the thermal radiation of the surface, and is sufficiently small compared with that of the monolithic plate. i.e., the high thermal resistance of truss members significantly reduces the heat being transferred to the inside surface. In addition, the shielding effect by ablation products reduces the input laser energy absorbed by SPTC. Thus, the damage to the inner structures can be reduced by using the sandwich panel with low relative density core. The heat shielding performance of the SPTC is similar to hypervelocity fragments shielding performance of Whipple in a space structure [30-32]. Although the shielding mechanism and engineering background are quite different, the basic principle is the same: sacrifice the outside structures and protect the inside structures with the minimum weight cost.

However, CW laser irradiates the inside surface of the SPTC directly when the outside surface is burned through. The temperature of the inside surface then dramatically increases and reaches the melting point. To further enhance laser resistance

performance, the void space of the truss core can be filled with lightweight thermal insulation or ablative material. It not only removes the effect of the thermal radiation between the two surfaces of SPTC, but also absorbs thermal energy generated by the CW laser irradiation through pyrolysis and phase change of the filler. Therefore, the filler in the truss core delays the time that the CW laser irradiates the inside surface, thereby improving the resistance of the SPTC to CW laser irradiation with little weight cost.

3. Filler material selection: a dimensional analysis

Filler material selection is a key issue to improve the laser resistance of the SPTC. A dimensional analysis is conducted to determine the efficient strategy for improving the resistance of the SPTC to high-power CW laser irradiation. Controlling parameters for structural response are deduced based on Pi theorem [33]. For simplicity, a single filler material is assumed in the theoretical model, as shown in Fig.3, and the following assumptions are made:

- (a) The energy absorbed by the material through laser irradiation is composed of latent heat and maximum sensible heat;
- (b) The laser absorption coefficient of the target is fixed at ε , and chemical reactions between the material and air are not considered;
- (c) The reference point of temperature rise is at the spot center of the inside surface.

According to these assumptions, the CW laser resistance of the target characterized

by the temperature rise of the inside surface T_{inside} , can be written as

$$T_{\text{inside}} = f(h, l; k, c, \rho, T_m, L; \varepsilon Q, t, r) \quad (1)$$

where Q , t , and r are laser power density, irradiation time t , and spot diameter, respectively. k , c , and ρ are thermophysical properties of the target material, which are thermal conductivity coefficient, specific heat, and density, respectively. T_m is the melting point, and L is the latent heat of fusion. h and l are the thickness and length of the target, respectively.

Taking target thickness h , density ρ , specific heat capacity c , and melting temperature T_m as a unit system, the following dimensionless relationship can be obtained:

$$\frac{T_{\text{inside}}}{T_m} = f\left(\frac{l}{h}; \frac{L}{\rho c T_m}, \frac{k}{\rho c^2 T_m^{\frac{3}{2}}}; \frac{\varepsilon Q}{\rho c T_m h}, \frac{t}{h \sqrt{c T_m}}, \frac{r}{h}\right) \quad (2)$$

Thermal diffusivity α measures the rate of heat transfer of a material from the hot side to the cold side, and it takes the form of ratio of the conducted thermal energy to the stored thermal energy [34]:

$$\alpha = \frac{k}{\rho c} \quad (3)$$

Enthalpy H at melting point characterizes the total stored thermal energy including sensible heat and latent heat:

$$H = \rho c T_m + L. \quad (4)$$

Then, Eq.2 can be written as:

$$\frac{T_{\text{inside}}}{T_m} = f\left(\frac{l}{h}, \frac{H}{\rho c T_m}, \frac{\alpha}{\sqrt{c T_m}}, \frac{\varepsilon Q}{\rho c T_m h}, \frac{t}{h^2 / \alpha}, \frac{r}{h}\right) \quad (5)$$

Physical significances of dimensionless parameters in Eq.5 are shown in Table 1.

For the given laser parameters and geometrical parameters of sandwich structures, the laser resistance of the filled sandwich structure depends on the parameters: $\frac{\alpha}{\sqrt{c T_m}}$, $\frac{H}{\rho c T_m}$ and $\frac{\varepsilon Q}{\rho c T_m h}$. The last two parameters can be written in an equivalent form $\frac{Hh}{\varepsilon Q}$ for a better view of physics. Then, two strategies can be obtained to enhance the laser resistance of the SPTC.

Based on the first parameter $\frac{\alpha}{\sqrt{c T_m}}$, the filler material should have lower thermal conductivity and higher density and specific heat. Taken the light-weight design of the SPTC into consideration, the thermal insulation material with low density is selected as one of filler materials. It prevents the heat energy stored in the outside surface to transfer into the inside surface.

$\frac{Hh}{\varepsilon Q}$ denote the ability of the target absorbing the laser energy. To reduce the laser damage to the inside equipment, the filler material should have higher enthalpy. Therefore filling the truss core with the ablative material, which has a higher latent heat and enthalpy, is another strategy to enhance the laser resistance of the SPTC.

The most widely used lightweight thermal insulation and ablative materials are shown in Fig.4. Regions surrounded by solid lines are thermal insulation materials, whereas those surrounded by dash lines are ablative materials. In the present work, the

compound of silicone resin and carbon powder, with a density of approximately 0.35–0.41 g/cm³ and conductivity of about 0.15–0.28 W/(m·K), and porous ceramic, which has a density of around 0.8–0.95 g/cm³ and conductivity of about 0.09–0.1 W/(m·K), are selected as the ablative material and thermal insulation material, respectively.

4. Experiments

4.1. Specimen preparation

As shown in Fig.5, three dimensional pyramidal truss cores are fabricated by using the folding method, which is simple, low-cost, and suitable for most metal truss cores compared with other fabrication techniques [35-37]. A punch-and-die pair of 60° angle was used to punch the nodal point of a 0.7 mm thick stainless steel wire mesh into a pyramidal type truss core with the side length of about 10 mm. The relative density of the truss core fabricated by this method is about 3%. Brazing technique is utilized to bond the truss core and solid facesheets. Then the fabricated sandwich panel are cut into 50 mm × 50 mm specimens. The thickness of the truss core and the facesheet are 7 mm and 0.9 mm, respectively.

In the experiment, four types of specimens are prepared and tested, i.e., solid plates, unfilled SPTCs, SPTCs filled with porous ceramic, and SPTCs filled with silicone resin and carbon powder.

As shown in Table 2, specimens denoted with "S1"–"S4" are SPTCs filled with porous ceramics. Additional weights were about 17.5 % of the unfilled SPTC. The

toothpaste-like ceramic putty in the initial state was inserted into the truss core and then solidified at room temperature to form the SPTC with porous ceramic fillers. Specimens denoted with "S5"–"S8" are SPTCs filled with the compound of the silicone resin combined with different carbon powder percentages. Additional weights were about 25 % of the unfilled SPTC. The fabrication process of this specimen is similar to those filled with porous ceramic. Figs.6(a)-(b) show fabricated specimens filled with the porous ceramic and the compound of silicone resin and carbon powder, respectively.

By contrast, monolithic stainless steel plates with approximately equal areal densities are fabricated, i.e., the thickness is 2.0, 2.3, 2.4 2.5 and 2.6 mm.

4.2 Experimental setup

The experimental setup is illustrated in Fig.7. To obtain the thermal response of the SPTC under laser irradiation, a thermal imager camera (TIC) with a resolution of 420×640 pixel was placed over the distance of the inside surface to measure the full-field temperature distribution. The sampling frequency was 30 Hz, and the temperature measurement range was 100–2700 °C. A multi-colorimetric pyrometer (MCP) over a range of 700–1800 °C was also used to verify the precision of the TIC. A CCD camera was placed inside the SPTC to derive the dynamic damage evolution of the back surface. The sampling frequency and resolution were 60 Hz and 1600×1200 pixel, respectively. A IPG YLS 2000 W fiber laser operating at 1.07 μm was utilized as the laser source. In the experiment, 1000 W output laser was adopted. The laser beam diameter was 10 mm, which can be obtained by adjusting the distance from the

specimen to the laser head. The distance between the specimen and the laser head was 875 mm.

5. Results and discussions

5.1 Temperature history and failure point

The target is failed when the melt front reaches the inside surface of the material with an external high-speed air flow or a substantial pressure difference between the outside and inside surfaces, which are typical loading conditions for TPS during service. In the present work, this period is referred to as the failure time of the specimen and was the basic measurement of the laser damage.

Fig.8 shows temperature histories of the inside surface of monolithic plates with a thickness range of 2.0–2.6 mm. In each test, the temperature of inside surface rises rapidly upon laser irradiation due to the high heat conduction along the thickness direction, and the melting point of about 1400 °C is reached after a few seconds (typically about 5 seconds). The temperature rise of the spot center maintains a steady state because of the surface tension of the molten material. The molten metal is then expelled from the target, which is referred to as the burn through time, and the measured temperature dropped abruptly. The two driving forces responsible for the melt expulsion are the recoil pressure and the Marangoni effect, which emerged from the non-uniform temperature distribution across the spot center [21]. Results show that the failure time and burned through time of monolithic plates are roughly in proportional to plate thickness.

Temperature histories of SPTCs filled with porous ceramic are presented in Fig.9.

The melting point of the facesheet of SPTCs is decreased during the high-temperature brazing process, and thus, the time the temperature reached the plateau state is supposed to be the failure time. The heat energy generated through CW laser irradiation is mainly consumed by the latent heat of melting the metallic SPTC and porous ceramic. The latent heat of melting the metallic material can be approximately expressed as

$$L_{m, \text{metal}} \approx RT_{m, \text{metal}}, \quad (5)$$

where R and T_m are the universal gas constant and the melting point, respectively. The latent heat of melting the ceramic material is [38]

$$L_{m, \text{ceramic}} \approx (3-4)RT_{m, \text{ceramic}}. \quad (6)$$

The melting point of the ceramic filler $T_{m, \text{ceramic}}$ is about 2000 °C, which is higher than that of the stainless steel, which is about 1400 °C. Therefore, porous ceramic cores can absorb more heat than stainless steel when they are in the same mass. In addition, the thermal insulation porous ceramic cores delays the time that the heat transferred to inside surfaces. In Fig. 9, no temperature rise is measured before 6.5 s, and the time to reach failure point is about 8.5–10 s, which is considerably longer than that of monolithic plates. However, the burn through time of the inside surface for this kind of structure is shorter than that of monolithic plates, due to the decreased surface tension of molten materials.

Fig.10 shows temperature histories of SPTCs filled with the compound of the silicone resin and carbon powder. It can be found that the measurable temperature of

inside surface is further delayed to about 10 s, and the time to reach failure point is delayed to about 20 s. Compared with the porous ceramic, pyrolysis, oxidation and sublimation occurred in the ablation process of the compound of silicone resin and carbon powder. On the one hand, the pyrolysis of the silicone resin can absorb a certain amount of heat energy generated by CW laser irradiation. On the other hand, the pyrolytic gas also takes away heat energy through forced convection, leaving porous structures with lower thermal conductivity, thereby delaying the heat transfer process [39, 40]. The sublimation of the carbon powder and pyrolytic residue also dissipate a significant amount of heat energy. Therefore, the ablation velocity of this material is lower than that of the porous ceramic. Consequently, the laser resistance of the SPTC can be further improved by filling the void space with ablative materials. In addition, increasing in the volume percentage of carbon powder can enhance the performance of the SPTC, however it results in slightly increase in the filler density.

Fig.11 gives inside surface temperature histories of structures with different configurations. For comparison, the response of the unfilled SPTC is also measured experimentally. The order of the laser resistance of the four structures is as follow: SPTC with the compound of silicone resin and carbon powder, SPTC filled with porous ceramic, unfilled SPTC, and monolithic plate. The thermal response time of unfilled sandwich structures is slower than that of monolithic plates due to the thermal resistance of the truss core. The shielding effect of thermal radiation due to fillers further delayed the thermal response time of the filled SPTC, resulting in a prolonged failure time

compared to the unfilled SPTC. However, the burn through time of the monolithic plate is longer than that of the unfilled SPTC and SPTC filled with ceramic, due to higher surface tension of molten materials. The burn through time of the SPTC filled with porous ceramic is shorter than that of the unfilled SPTC, because of the absorption effect of the porous ceramic to the molten material.

5.2 Full-field temperature and damage evolution

As shown in Fig.12, the superior resistance of the sandwich structure to high-power laser irradiation can also be found from full-field temperature evolutions of the inside surface, especially those filled with ablative materials.

For monolithic plate, the temperature rises rapidly upon laser irradiation, and the range of high temperature zone also grows rapidly, which is larger than the other cases. The melting zone range expands and expulses from the plate at 18.5 s.

The inside surface of unfilled sandwich structures is in its initial state even at an irradiation time of 5 s. At 5.5 s, heat transfer to the inside surface through the combined effect of heat conduction by truss members and thermal radiation by the hot outside facesheet. When the molten metal is expulsed from the outside surface, the laser irradiates the inside surface directly. Then the temperature of the inside surface and the range of melting zone grows rapidly.

For structures at fixed laser irradiation time, such as 10 s, the inside surface has an evident melting zone for the monolithic plate, the unfilled SPTC and the SPTC filled with porous ceramic. However, the laser-induced damage in the inside surface is

negligible for SPTCs filled with the compound of silicone resin and carbon powder. In addition, heat affected zones in the inside surface of SPTCs with fillers are smaller than those of monolithic plates and unfilled SPTCs when they are burned through, see last frames in each structure in Fig.12. Fig.13 shows the dynamic failure process of structures with different configurations obtained by CCD camera. A similar conclusion can be found from the failure process, wherein the performance of sandwich structures under CW laser irradiation is better than that of monolithic plates, especially for SPTCs filled with ablative materials.

5.3 Laser resistance versus density

The comparison of measured failure times across the four kinds of structures with different areal densities are shown in Fig.14. At the same equivalent areal density, the failure time of monolithic plate is the shortest, which means a poor laser resistance performance. The unfilled SPTC is slightly higher than the monolithic plate. Laser resistance performance of the SPTC can be obviously improved by filling the void space of the panel with thermal insulation materials, and can be dramatically improved when it is filled with ablative materials. The slope of the fitting line for the failure time of the filled SPTC is higher than the monolithic plate. It means that the monolithic plate need more weight lost than the filled SPTC to enhance the laser resistance.

The extent of the laser damage in the inside surface is another means of evaluating the resistance of structures to CW laser. Fig.15 shows the diameter of the melt hole in the inside surface. For monolithic plates, there is little thermal resistance in the

through-thickness direction, thus the damage in the inside surface is serious. The SPTC filled with the compound of silicone resin and carbon powder has the smallest laser damage even with its long irradiation time, due to the absorption of the ablative material to the heat generated by the CW laser.

5.4 Laser ablation morphology and failure mechanism

Fig.16 compares the ablation morphologies between the outside and inside surfaces for structures with different configurations. Some white annular regions around the ablation hole in the inside surface refer to the oxidation of the speckle paint, which represents the range of high temperature zone. Similar tendency can be found that SPTCs filled with thermal insulation and ablative materials have smaller high temperature zones compared with monolithic plates and unfilled SPTCs.

The detailed morphology of the ablation hole for filled SPTCs is shown in Fig.17. For SPTCs filled with porous ceramic, Figs.17(a)-(b) indicates that the molten metallic and porous ceramic gathered around the wall of the ablation hole and then solidified, forming some micro holes with a diameter of about 1 mm. The solution accelerated the damage process, wherein the metallic solution expelled from the irradiated area in the inside surface. The morphology of the SPTC filled with the compound of silicone resin and carbon powder is shown in Figs.17(c)-(d), with a number of white columnar ablation residues placed around the wall of the ablation hole. The ingredient of the white ablative residue, which is formed by the oxidation of the silicone resin pyrolysis product, is silicon dioxide. Cross-sectional view of this type of specimen after laser

irradiation is shown in Fig.18. The examination of the specimen indicates that the pyrolysis of the silicone resin in high temperature generated some black and sloppy structures around the ablation hole. The diameter of the pyrolysis region is about three times of that of the ablative hole. The entire layout of the ablation hole is characterized by massive damage in the outside surface and minimal inside, thereby reducing the laser damage to the inner equipment.

6. Conclusions

This work presents an experimental analysis of the performance of SPTCs irradiated by a high-power CW laser with fixed intensity. Two kinds of materials, including porous ceramic and the compound of silicone resin and carbon powder, are filled in the void space of the sandwich panel to further enhance the laser resistance of the SPTC. Full-field temperature distribution and dynamic ablation process are measured by thermal infrared imager and CCD camera, respectively. Experimental results show that the performance of sandwich structures under high-power laser irradiation is superior than that of monolithic plates due to the heat resistance of the truss core. Filling cores with thermal insulation and ablative materials not only increases the failure time of SPTC, but also decreases the extent of ablation damage. The laser damage for SPTCs filled with the compound of silicone resin and carbon powder is smaller than those filled with porous ceramic because of the high absorption ability to the heat energy. The sequence of structural resistance to high-power laser irradiation is as follows: SPTC filled with the compound of silicone resin and carbon powder, SPTC

filled with porous ceramic, unfilled SPTC, and monolithic plate. In the subsequent works, we will develop a numerical model to get the quantitative relationship between the laser resistance of the filled SPTC and the thermophysical properties of the ablative material according to the detailed ingredient of the ablative residue measured by the infrared spectrum and the scanning electron microscope image.

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References

- [1] Froend M, Fomin F, Riekehr S, Alvarez P, Zubiri F, Bauer S, et al. Fiber laser welding of dissimilar titanium (Ti-6Al-4V/cp-Ti) T-joints and their laser forming process for aircraft application. *Optics and Laser Technology*. 2017;96:123-31.
- [2] Zhou L, Li ZY, Song XG, Tan CW, He ZZ, Huang YX, et al. Influence of laser offset on laser welding-brazing of Al/brass dissimilar alloys. *Journal of Alloys and Compounds*. 2017;717:78-92.
- [3] Marimuthu S, Antar M, Dunleavey J, Chantzis D, Darlington W, Hayward P. An experimental study on quasi-CW fibre laser drilling of nickel superalloy. *Optics and Laser Technology*. 2017;94:119-27.
- [4] Moradi M, Mehrabi O, Azdast T, Benyounis KY. Enhancement of low power CO₂ laser cutting process for injection molded polycarbonate. *Optics and Laser Technology*. 2017;96:208-18.
- [5] Gan ZT, Yu G, He XL, Li SX. Numerical simulation of thermal behavior and multicomponent mass transfer in direct laser deposition of Co-base alloy on steel. *International Journal of Heat and Mass Transfer*. 2017;104:28-38.
- [6] Ma Y, Xu B, Chen M, He R, Wen W, Cheng T, et al. Optimization design of built-up thermal protection system based on validation of corrugated core homogenization. *Applied Thermal Engineering*. 2017;115:491-500.
- [7] Wei K, Cheng X, Mo F, Wen W, Fang D. Design and analysis of integrated thermal protection system based on lightweight C/SiC pyramidal lattice core sandwich panel. *Materials & Design*. 2016;111:435-44.
- [8] Ashby MF, Brechet YJM. Designing hybrid materials. *Acta Materialia*. 2003;51:5801-21.
- [9] Fleck NA, Deshpande VS. The resistance of clamped sandwich beams to shock loading. *Journal of Applied Mechanics-Transactions of the Asme*. 2004;71:386-401.
- [10] Kooistra GW, Deshpande VS, Wadley HNG. Compressive behavior of age hardenable tetrahedral lattice truss structures made from aluminium. *Acta Materialia*. 2004;52:4229-37.
- [11] Radford DD, Fleck NA, Deshpande VS. The response of clamped sandwich beams

- subjected to shock loading. *International Journal of Impact Engineering*. 2006;32:968-87.
- [12] Rathbun HJ, Radford DD, Xue Z, He MY, Yang J, Deshpande V, et al. Performance of metallic honeycomb-core sandwich beams under shock loading. *International Journal of Solids and Structures*. 2006;43:1746-63.
- [13] Yan LL, Yu B, Han B, Chen CQ, Zhang QC, Lu TJ. Compressive strength and energy absorption of sandwich panels with aluminum foam-filled corrugated cores. *Composites Science and Technology*. 2013;86:142-8.
- [14] Han B, Yu B, Xu Y, Chen CQ, Zhang QC, Lu TJ. Foam filling radically enhances transverse shear response of corrugated sandwich plates. *Materials & Design*. 2015;77:132-41.
- [15] Ni CY, Hou R, Xia HY, Zhang QC, Wang WB, Cheng ZH, et al. Perforation resistance of corrugated metallic sandwich plates filled with reactive powder concrete: Experiment and simulation. *Composite Structures*. 2015;127:426-35.
- [16] Yungwirth CJ, Radford DD, Aronson M, Wadley HNG. Experiment assessment of the ballistic response of composite pyramidal lattice truss structures. *Composites Part B-Engineering*. 2008;39:556-69.
- [17] Yazici M, Wright J, Bertin D, Shukla A. Experimental and numerical study of foam filled corrugated core steel sandwich structures subjected to blast loading. *Composite Structures*. 2014;110:98-109.
- [18] Karttunen AT, Kanerva M, Frank D, Romanoff J, Remes H, Jelovica J, et al. Fatigue strength of laser-welded foam-filled steel sandwich beams. *Materials & Design*. 2017;115:64-72.
- [19] Wu CW, Wu XQ, Huang CG. Ablation behaviors of carbon reinforced polymer composites by laser of different operation modes. *Optics and Laser Technology*. 2015;73:23-8.
- [20] Jelani M, Li ZW, Shen ZH, Sardar M. Failure Response of Simultaneously Pre-Stressed and Laser Irradiated Aluminum Alloys. *Applied Sciences-Basel*. 2017;7.
- [21] Volkov AN, Zhigilei LV. Melt dynamics and melt-through time in continuous wave laser heating of metal films: Contributions of the recoil vapor pressure and Marangoni effects.

- International Journal of Heat and Mass Transfer. 2017;112:300-17.
- [22] Crane KCA, Garnsworthy RK, Mathias LES. Ablation of Materials Subjected to Laser-Radiation and High-Speed Gas-Flows. *Journal of Applied Physics*. 1980;51:5954-61.
- [23] Johnson RL, Okeefe JD. Laser Burnthrough Time Reduction Due to Tangential Air-Flow - Interpolation Formula. *Aiaa Journal*. 1974;12:1106-9.
- [24] Okeefe JD, Johnson RL. Laser Melt through Time Reduction Due to Aerodynamic Melt Removal. *Aiaa Journal*. 1976;14:776-80.
- [25] Robin JE, Nordin P. Enhancement of Cw Laser Melt-through of Opaque Solid Materials by Supersonic Transverse Gas-Flow. *Applied Physics Letters*. 1975;26:289-92.
- [26] Robin JE, Nordin P. Reduction of Cw Laser Melt-through Times in Solid Materials by Transverse Gas-Flow. *Journal of Applied Physics*. 1975;46:2538-43.
- [27] Boley CD, Cutter KP, Fochs SN, Pax PH, Rotter MD, Rubenchik AM, et al. Interaction of a high-power laser beam with metal sheets. *Journal of Applied Physics*. 2010;107.
- [28] Huang YH, Song HW, Huang CG. Heat Transfer and Mode Transition for Laser Ablation Subjected to Supersonic Airflow. *Chinese Physics Letters*. 2016;33.
- [29] Yuan W, Song HW, Lu LL, Huang CG. Effect of local damages on the buckling behaviour of pyramidal truss core sandwich panels. *Composite Structures*. 2016;149:271-8.
- [30] Huang X, Ling Z, Liu ZD, Zhang HS, Dai LH. Amorphous alloy reinforced Whipple shield structure. *International Journal of Impact Engineering*. 2012;42:1-10.
- [31] Ryan S, Christiansen EL. Hypervelocity impact testing of advanced materials and structures for micrometeoroid and orbital debris shielding. *Acta Astronautica*. 2013;83:216-31.
- [32] Zhang XT, Liu T, Li XG, Jia GH. Hypervelocity impact performance of aluminum egg-box panel enhanced Whipple shield. *Acta Astronautica*. 2016;119:48-59.
- [33] Tan QM. Dimensional analysis. With case studies in mechanics. Berlin Heidelberg. 2011.
- [34] Bergman TL, Lavigne AS, Incropera FP, Dewitt DP. Fundamentals of Heat and Mass Transfer. 2011.
- [35] Deshpande VS, Fleck NA, Ashby MF. Effective properties of the octet-truss lattice material.

Journal of the Mechanics and Physics of Solids. 2001;49:1747-69.

[36] Park JS, Joo JH, Lee BC, Kang KJ. Mechanical behaviour of tube-woven Kagome truss cores under compression. International Journal of Mechanical Sciences. 2011;53:65-73.

[37] Wadley HNG, Fleck NA, Evans AG. Fabrication and structural performance of periodic cellular metal sandwich structures. Composites Science and Technology. 2003;63:2331-43.

[38] Li Q. Damage effects of vehicles irradiated by intense lasers. Bei Jing, China: China Astronautic Publishing House, 2012.

[39] Dimitrienko YI. Thermomechanics of Composites under High Temperatures. Solid Mechanics & Its Applications. 1999.

[40] Lundell J, Dickey R. The response of heat-shield materials to intense laser radiation. Aiaa Journal. 1978;64:1-8.

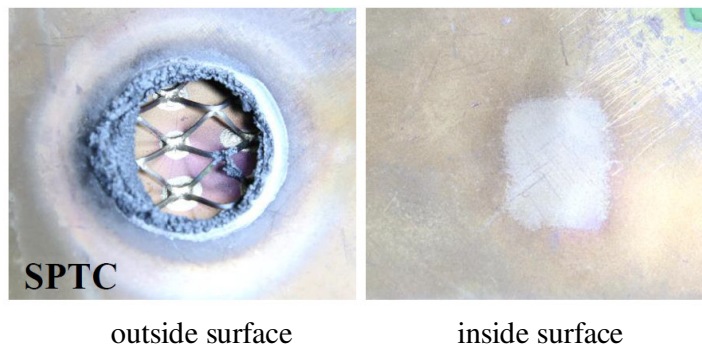


Fig.1 The response of the SPTC irradiated by high-power CW laser.

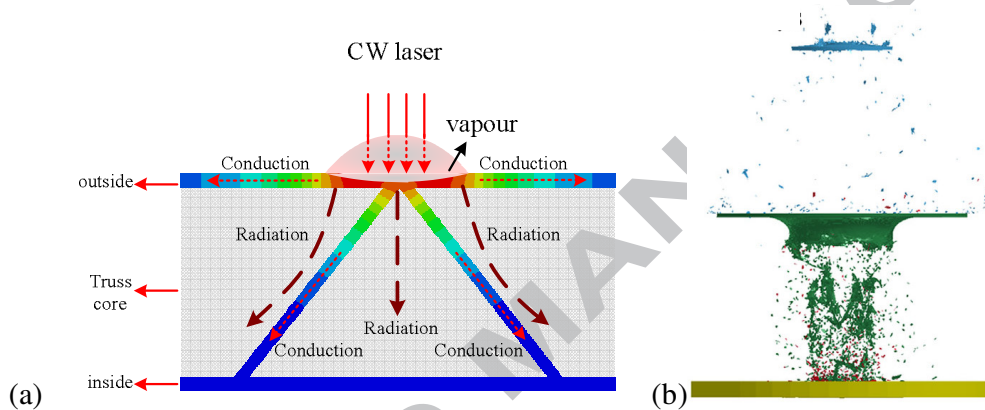


Fig.2 CW laser resistance mechanisms of the SPTC in analogy to hypervelocity of the Whipple shield. (a) laser heat shielding of SPTC, (b) hypervelocity fragment shielding of Whipple [32].

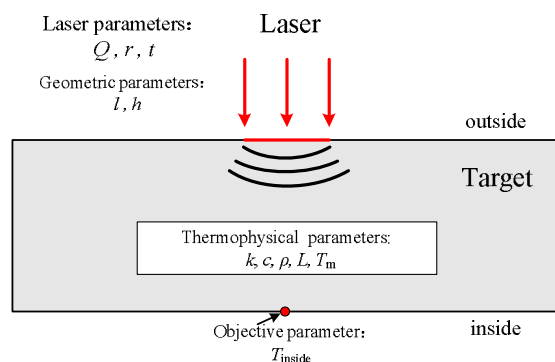


Fig.3 Illustration of dimensional analysis: laser parameters, target parameters and objective parameter.

Table1 Physical significances of dimensionless parameters in the dimensional analysis

Parameters	Physical significance
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$\frac{l}{h}$	geometrical characteristics
$\frac{H}{\rho c T_m}$	ratio of total stored energy to maximum sensible heat
$\frac{\alpha}{\sqrt{c T_m}}$	ratio of thermal diffusivity to the maximum sensible heat capacity
$\frac{\varepsilon Q}{\rho c T_m h}$	ratio of laser energy deposition to the heat storage capacity of materials
$\frac{t}{h^2 / \alpha}$	Fourier number
$\frac{r}{h}$	ratio of geometrical characteristics of the laser spot area to the thickness of the target

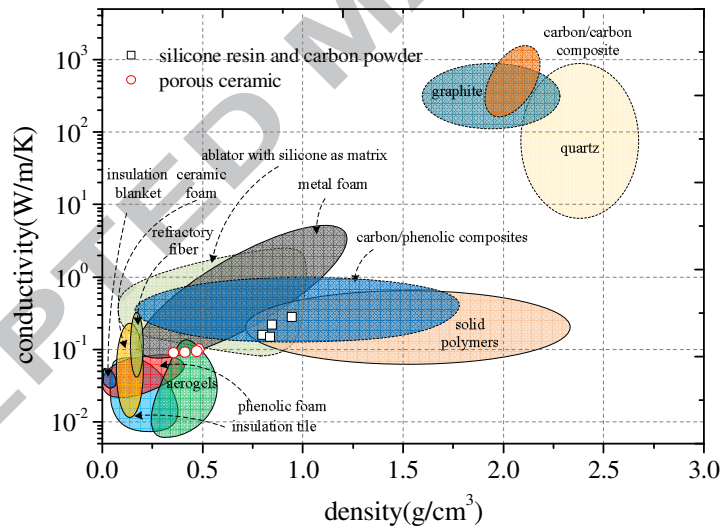


Fig.4 Thermal conductivities of lightweight ablative and thermal insulation materials to be filled in the SPTC

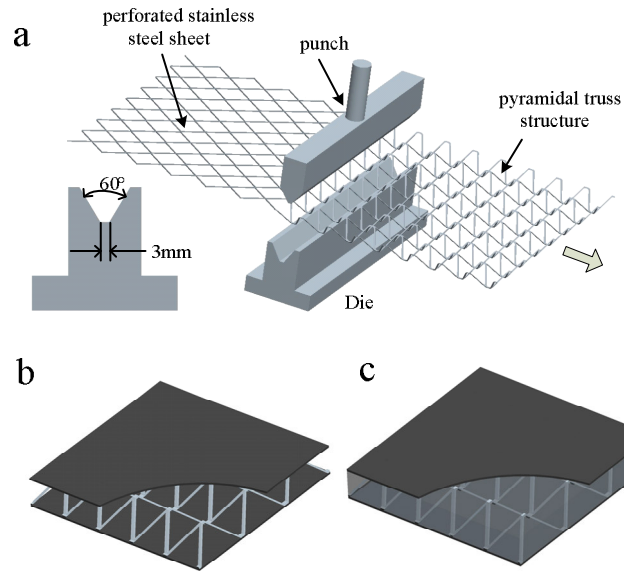
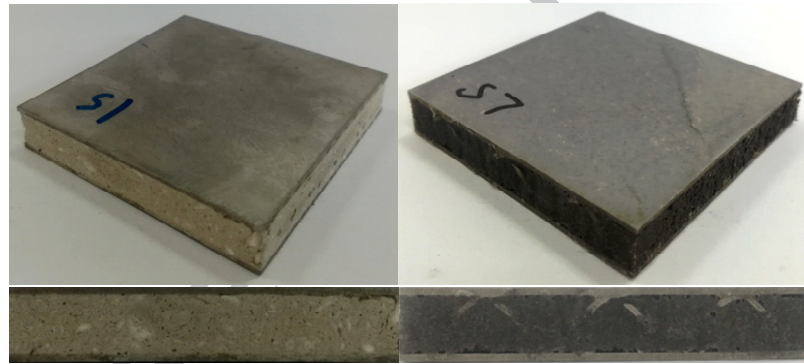


Fig.5 Preparation of truss core sandwich panels with fillers: (a) punching truss cores; (b) unfilled sandwich panel; (c) sandwich panels with fillers.



porous ceramic

silicone resin and carbon powder

Fig.6 Fabricated sandwich panels filled with thermal insulation and ablative materials

Table 2 Weight of the unfilled and filled SPTC

	S1	S2	S3	S4	S5	S6	S7	S8
Unfilled SPTC	40.2g	40.3g	40.5g	40.6g	40.2g	40.4g	40.4g	40.0g
Filled SPTC	46.1g	47.7g	47.8g	47.1g	50.1g	49.8g	51.1g	49.8g

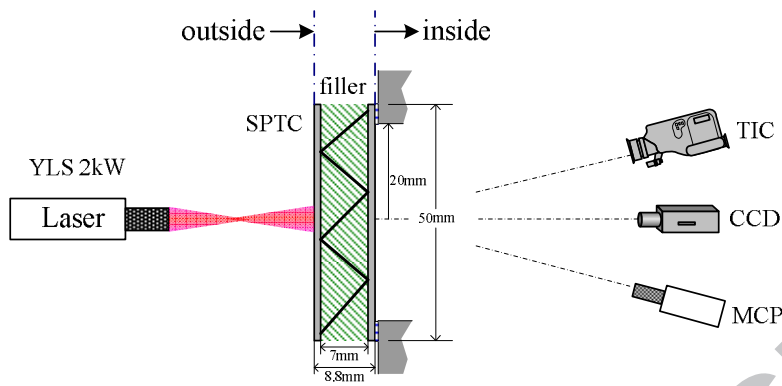


Fig.7 Experimental setup sketch

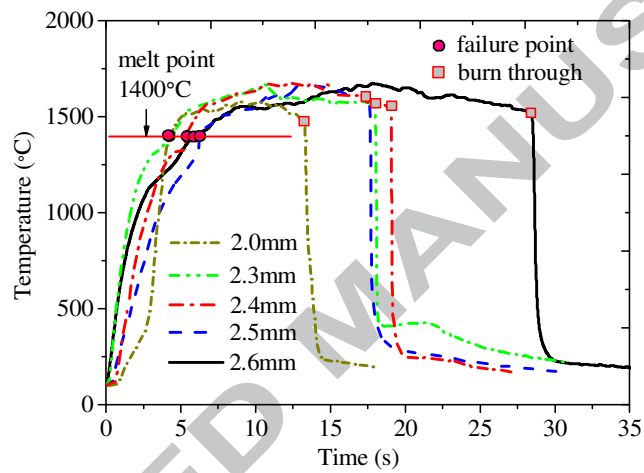


Fig.8 Inside surface temperature histories of monolithic plates under CW laser irradiation.

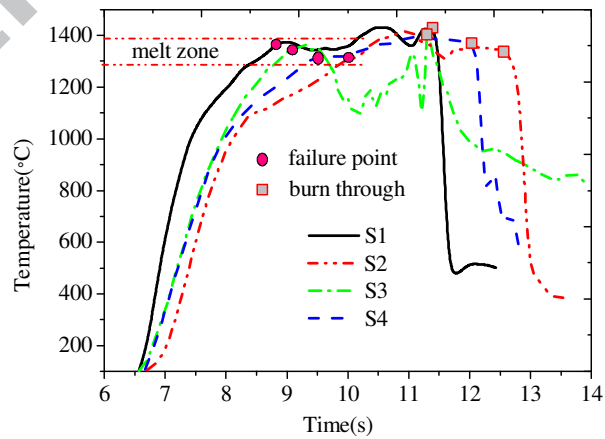


Fig.9 Inside surface temperature histories of sandwich panels filled with porous ceramic.

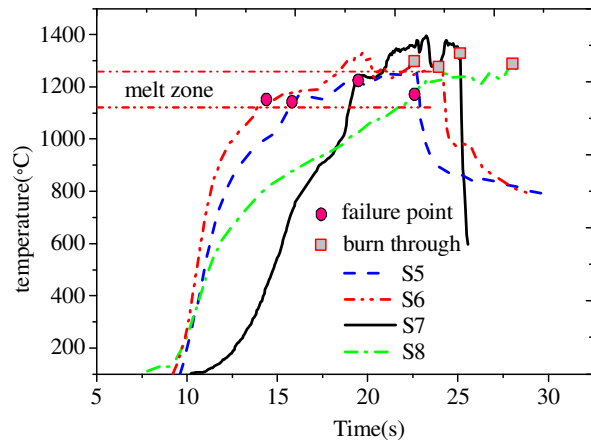


Fig.10 Inside surface temperature histories of sandwich panels filled with organic silicon and carbon powder.

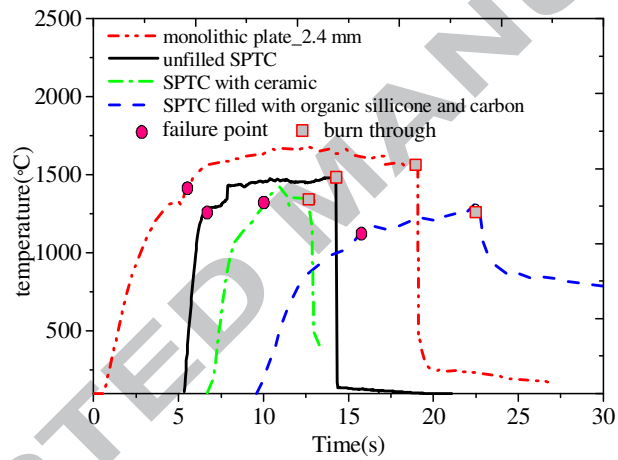


Fig.11 Comparison of temperature histories of monolithic plate, unfilled SPTC, SPTC with ceramic, and SPTC with organic silicone and carbon powder.

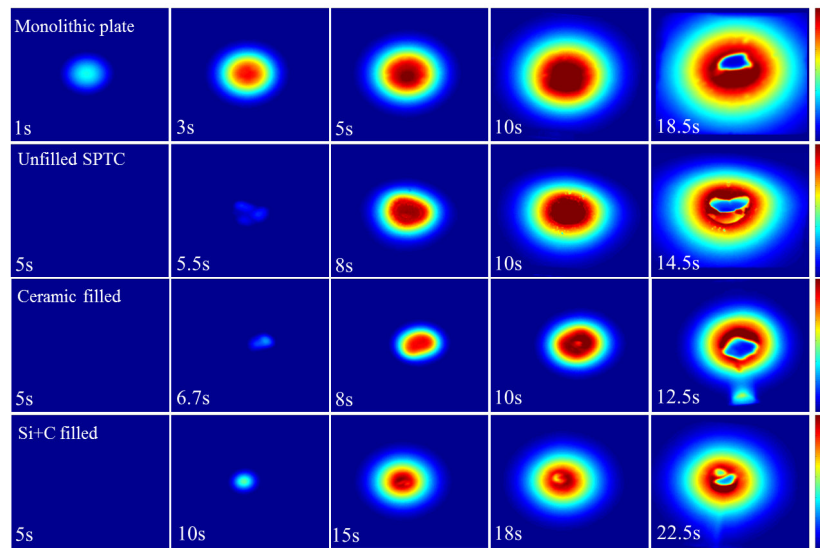


Fig.12 Temperature distribution in the inside surface at different irradiation time, obtained by a thermal imaging camera.

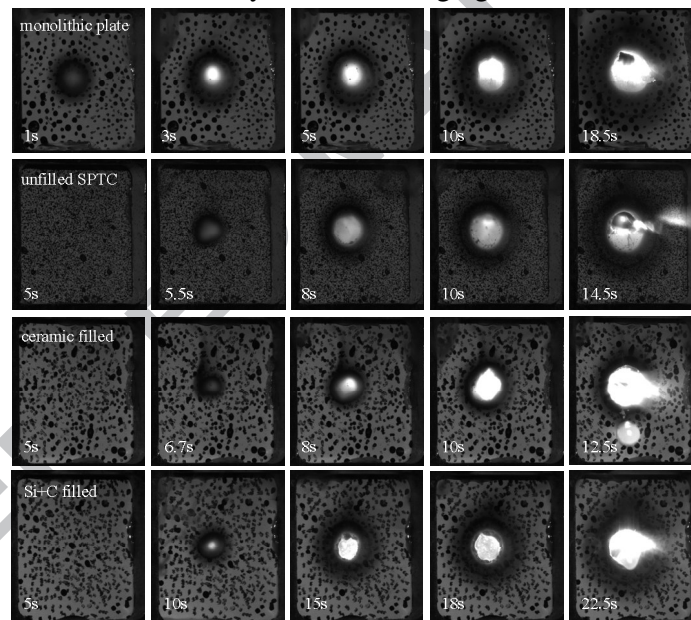


Fig.13 Failure process of the inside surface at different time captured by CCD camera.

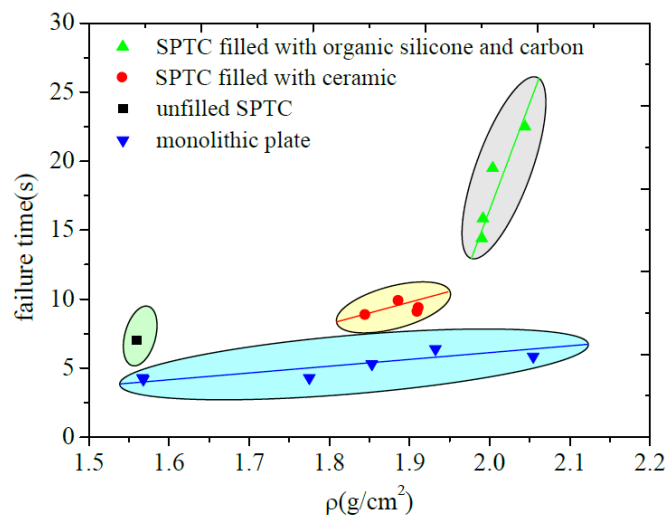


Fig.14 Comparison of failure time of monolithic plate, unfilled SPTC, SPTC with ceramic, SPTC with compound of organic silicon and carbon powder. Irradiated with laser power $P=1000$ W, and spot diameter 10 mm.

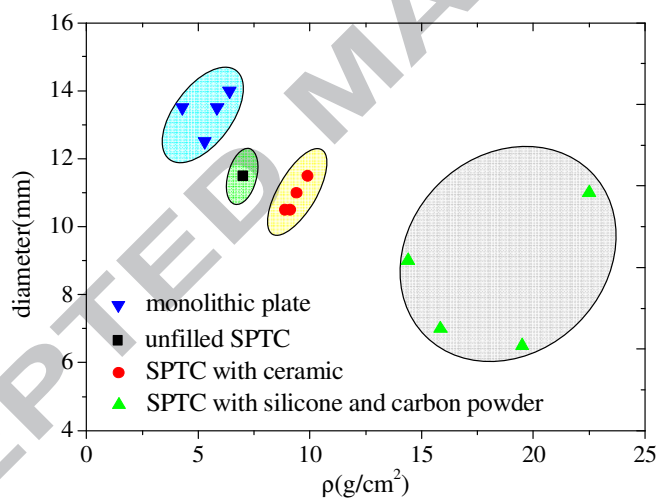


Fig.15 Diameters of the melt zone in the inside surface of structures with different configurations.

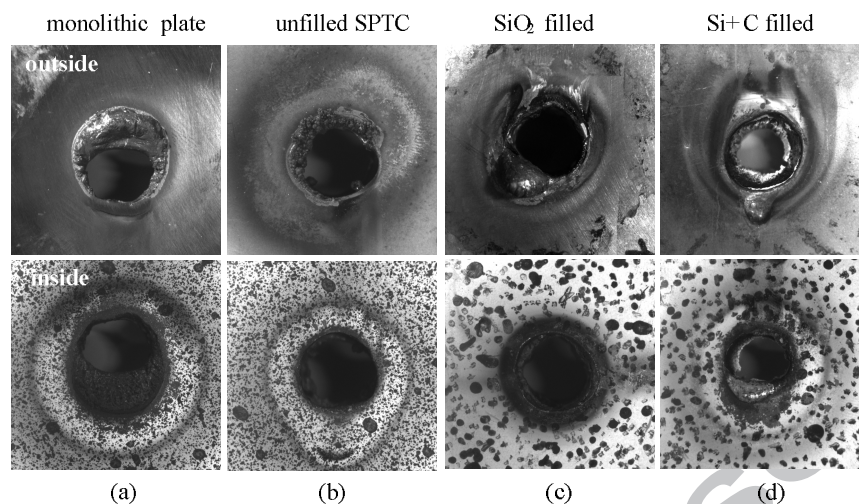


Fig.16 Comparison of the ablation morphologies between the outside and inside surfaces for structures with different configurations: (a) monolithic plate; (b) unfilled SPTC; (c) SPTC filled with ceramic; (d) SPTC filled with compound of organic silicone and carbon powder.

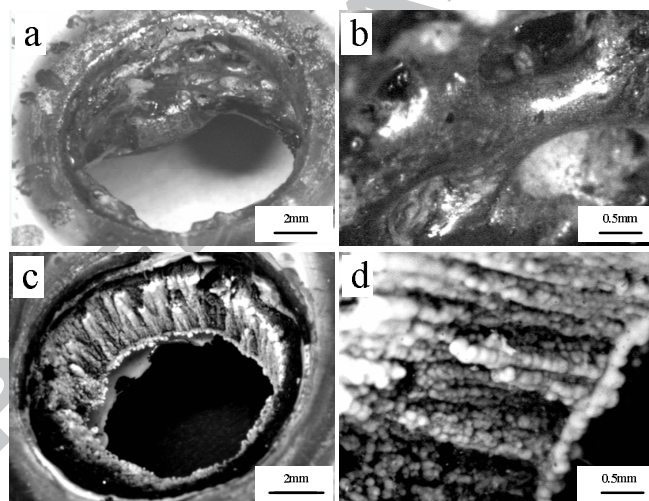


Fig.17 Ablation morphologies of SPTC with fillers: (a)–(b) SPTC filled with ceramic, (c)–(d) SPTC filled with organic silicone and carbon powder.

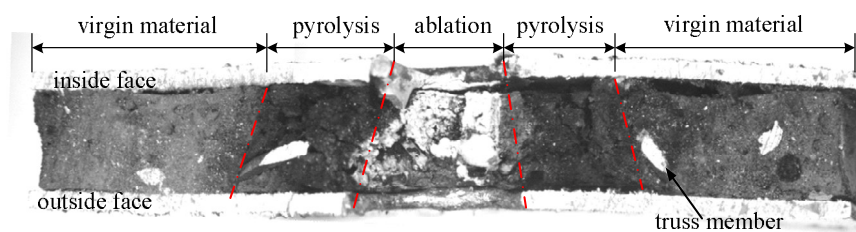


Fig.18 Cross-sectional view of the SPTC filled with the compound of silicone resin and carbon powder after laser irradiation.