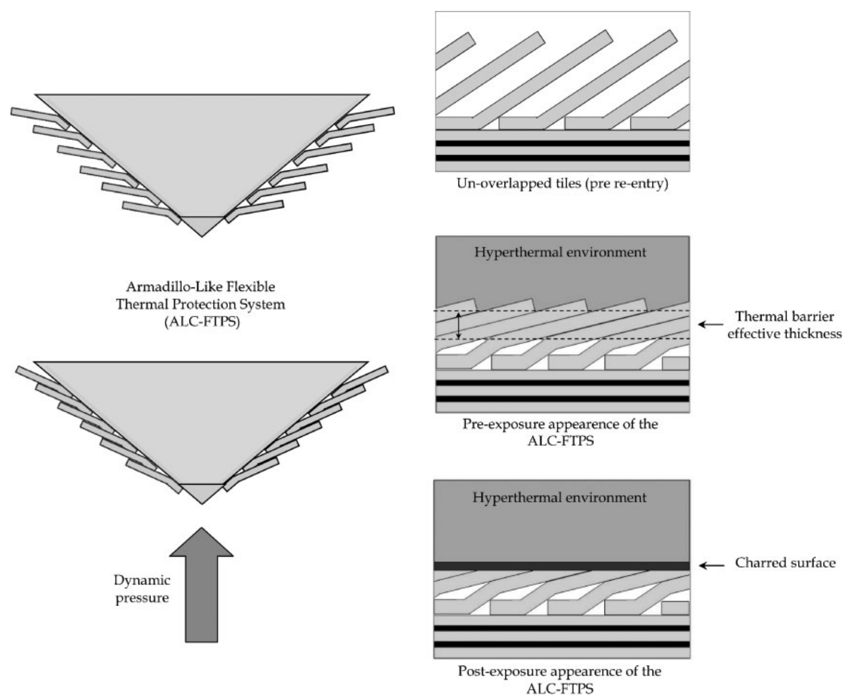
An Armadillo-Like Flexible Thermal Protection System for Inflatable Decelerators: A Novel Paradigm

Maurizio Natali, Marco Rallini, Debora Puglia, Josè Kenny, Luigi Torre*

Polymeric ablative materials play a strategic role in the whole aerospace industry: they are used to produce the thermal protection system (TPS), which protects vehicles during the hypersonic flight through a planetary atmosphere. To date, TPSs are typically designed as rigid monolithic heat shields. Inflatable deployable aeroshells (IDAs) offer an alternative to rigid TPSs: IDAs are based on the use of flexible TPSs (FTPSs). State of the art FTPSs can handle heat fluxes up to approximately 20 W cm^{-2}. However, next generation FTPSs for IADs should be able to survive heat fluxes up to 150 W cm^{-2}. To satisfy these stringent requirements, we propose a radically brand-new paradigm of flexible TPS based on the use of state of the art elastomeric ablatives (EPDM/Aramid) employed to produce the insulation liners for solid rocket motors. This class of ablatives is able to survive heat fluxes in the range of (300–1000) W cm^{-2}. Most important, we envisioned to introduce an "Armadillo-Like" design in which a series of overlapping sacrificial movable tiles could work as a continuous flexible thermal barrier.



Dr. M. Natali, Dr. M. Rallini, Dr. D. Puglia, Prof. J. Kenny, Prof. L. Torre
University of Perugia, INSTM, Perugia Research Unit 05100, Terni, Italy
E-mail: torrel@unipg.it

1. Introduction

1.1. Flexible Thermal Protection Systems: State of the Art

Polymeric ablative materials (PAMs) play a strategic role in the whole aerospace industry: they are used to produce the

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thermal protection system (TPS) which protects the structures, the aerodynamic surfaces, and the payload of vehicles and probes during the hypersonic flight through a planetary atmosphere.[1,2] PAMs are also used to manufacture passively cooled rocket combustion chambers[3] and to provide thermal protection to propulsion devices such as solid rocket motors (SRMs).[4,5] Such a wide range of heat shields is generally produced using reinforced thermosets[2] or elastomers:[4–15] a wide literature survey on the different types of PAMs was provided by Natali et al.[2] To date, TPSs are typically designed as rigid aeroshell systems (RASs), i.e., as a rigid monolithic heat shields (Figure 1a). However, the technology of RASs is rapidly approaching its limit: in fact, even considering the larger launchers, the payload fairing of the rocket (the payload fairing of a rocket is the nose cone, the volume of the vehicle which hosts the satellite or the probe) strongly limits the diameter of the TPS. Inflatable deployable aeroshells (IDAs; Figure 1b) offer an alternative to rigid TPSs: IDAs are based on the use of flexible TPSs (FTPSs). Initial studies on IDAs indicate that these systems would require a smaller payload mass fraction than traditional rigid aeroshell TPSs.[16] Inflatable aeroshells would also require a smaller payload volume fraction than traditional rigid TPSs: in fact, the packaging flexibility of an inflatable system enables a more efficient use of the available payload volume. Another benefit of IDAs derives from the ability of the inflatable systems to produce ballistic coefficients significantly lower than those related to a rigid system: because of the low ballistic coefficient obtainable with inflatable aeroshells, the heat of entry is significantly reduced for the same payload mass.

Among efforts devoted to develop FTPSs, the Aeronautical Research Mission Directorate Hypersonic Project at NASA was one of the first and most relevant initiatives to study advanced high temperature FTPS to be used as hypersonic inflatable aerodynamic decelerators (HIADs). One of the primary goal of this program was to produce a first generation FTPS able to withstand an heat flux equal to 20 W cm^{-2}. Different TPS layups were designed, including the baseline configuration for the inflatable re-entry vehicle experiment-3 (IRVE-3) which, to date, represents the most advanced attempt to produce an inflatable FTPS. Accordingly, this baseline layup TPS was designed to withstand a

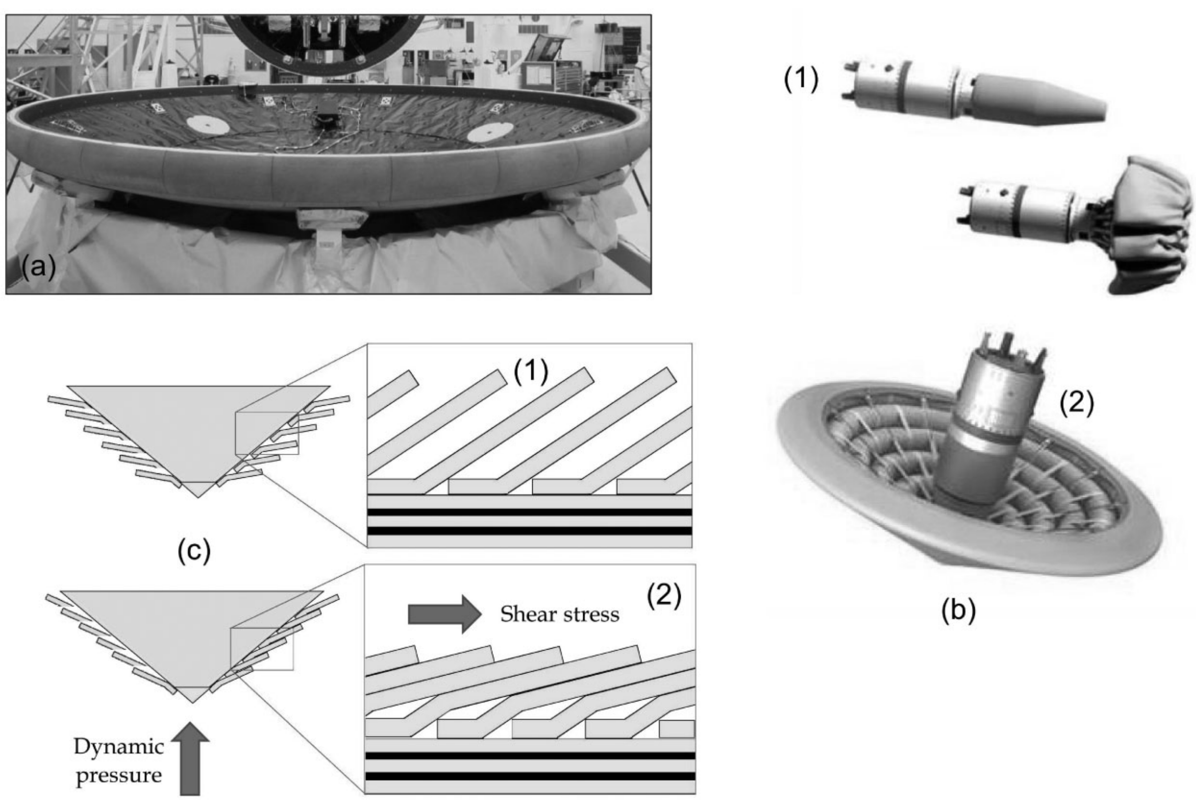

Figure 1. Appearance of a TPS as a rigid aeroshell systems (RAS) (a). Example of an inflatable deployable aeroshell (IDA) (b). Design of the deflated IRVE-3 IAD in a packed and stowed state (b_1 and b_2) as fully deployed heat shield. c) Armadillo-like configuration (ALC) in which the main heat pulse is shielded by a series of flexible, overlapping tiles made of EPDM/Aramid: fully deployed inflatable TPS with each single tile in an open state (c_1) and tiles compacted and overlapped one each other to form a continuous barrier (c_2). Notes: for image (a) and (b) the authors wish to acknowledge NASA.

heat flux of 20 W cm^{-2}: the obtained configuration was evaluated with different facilities.[17] A typical flexible aeroshell is comprised of structural and TPS components. The structure of IRVE-3 (Figure 1b) is constituted by a series of stacked inflatable torus tied to each other and to the vehicle with a network of straps: once deployed, these straps are in charge to maintain the desired shape of the aeroshell under the influence of the aerodynamic load. The flexible TPS is constructed from high temperature fabrics, insulators, and a gas barrier (Figure 2a,b). The TPS protects the inflated structure and the vehicle from the aerothermal environment. The current design for the IRVE-3 aeroshell (Figure 1b_2), consists of a 3 m diameter fully deployed heat shield, with a 60° half angle cone configuration in which the TPS is integrated on the fore body. The IRVE-3 flight aeroshell was required to withstand three hard packs without significantly damaging the aeroshell or negatively affects the performance of the TPS during the re-entry phase. A hard pack is the packed and stowed state of the deflated aeroshell (Figure 1b_1). The necessity to withstand three hard packs was derived from the ground operations prior flight, which includes an integrated systems test with deployment of the aeroshell from the stowed configuration, followed by a single hard pack for flight. The third hard pack is required in the unlikely situation in which a second integrated systems test was necessary. Combined with the necessity to withstand the packing process, the TPS layup for the inflatable aeroshell must also be able to survive very small bending radii. Moreover, the whole structure must ensure the correct deployment after exposure to relevant mission environments, without significant changes in the thermal and physical properties of the TPS. IRVE-3 was successfully tested during 2012: the experiment showed the enormous operational flexibility and the potential of this FTPS. In fact, even if the fully deployed heat shield reached a diameter of 3 m, the packed system was launched with a small and cheap sounding rocket (a Black Brant 9), a launcher with a payload fairing of about 0.5 m.

The detailed design of the IRVE-3 baseline TPS[17] is showed in Figure 2a,b. It is composed by two layers of Nextel BF-20 outer fabrics, which are directly exposed to entry aerodynamic environments: their function is to reduce or eliminate the hot gas impingement and the aerodynamic shear on the underlying plies. Pyrogel 3350 insulator layers manage the transferred heat load and are designed and tailored to maintain the TPS backside temperatures at values compatible with the inflatable structure. The Kapton/Kevlar laminate serves both as a TPS and as a structural component. In fact, Kapton works as an impermeable barrier: it allows to stop the flow path through the TPS, thus reducing or eliminating the potential

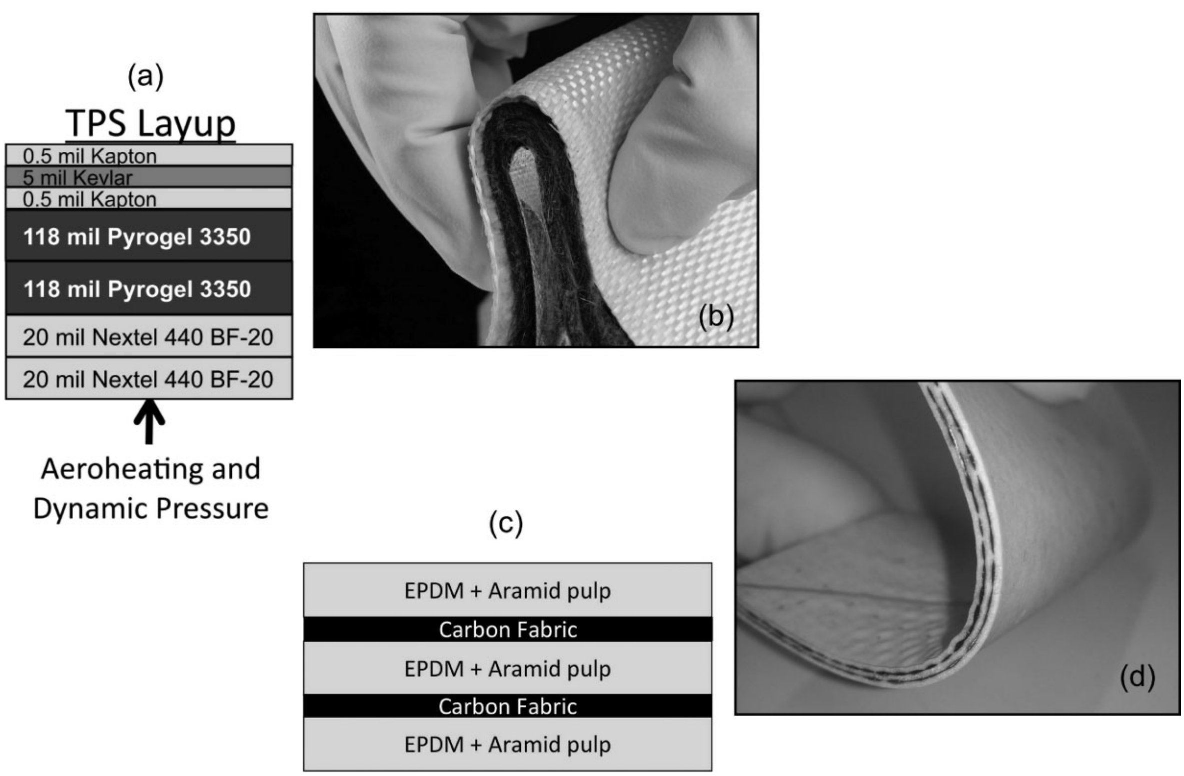

Figure 2. Detailed design of the IRVE-3 baseline TPS (a) and (b). Layup of the proposed elastomeric flexible composite (c and d). Notes: for image (a) and (b) the authors wish to acknowledge NASA.

for hot gas inflow through the TPS laminate. The Kevlar layer provides the mechanical interface for the anchoring of the TPS assembly to the inflatable structure. 3M Nextel Ceramic Fibers 440 (Nextel BF-20) are alumino-boro-silicate fibers. These fibers are woven into fabrics that retain strength with a limited shrinkage at continuous temperatures up to 1 370 °C. Pyrogel is a low density, high-temperature flexible insulation blanket made of silica gel and of non-woven carbon and glass fiber felt. DuPont Kapton is made of a polyimide film. Kapton can withstand temperatures as low as 269 °C and as high as 400 °C, and still retain its properties: however, at high temperatures, tensile performance decreases.

1.2. Working Principles of the Proposed Flexible TPS

As a matter of fact, to date, the IRVE-3 baseline constitutes the state of the art configuration and paradigm for FTPSs: the above-described layup represents the benchmark for any alternative design. As previously highlighted, this layup was studied and tested to survive at an heat flux of 20 W cm^{-2}. However, according to recent guidelines provided by agencies such as NASA,[18] the next generation FTPSs for deployable aerodynamic decelerators should be able to survive a single or dual heating exposure, with the first (or single pulse) having an heat fluxes of 50–150 W cm^{-2}: obviously, the new materials may be either flexible or deployable. Accordingly, the design proposed and tested on the IRVE-3 must be revised and replaced with a new paradigm able to manage higher heat fluxes. How to address the solution of is problem then? The original concept here presented deals with two main tenets.

The first one is represented by the use of elastomeric heat shielding materials (EHSMs) generally used to produce the liners of SRMs.[4] Why an EHSM can constitute an ideal candidate for the production of a flexible TPS? The reason will be clear very shortly. First of all, it is necessary to describe the traditional application of EHSMs, thus to understand the alternative use envisioned for this class of ablatives. A SRM case is conventionally manufactured from metals or carbon/epoxy filament wound composite: an ablative liner made of EHSMs is placed between the case and the solid fuel grain.[19] The primary function of the internal insulation is to prevent the rocket motor case from reaching temperatures that may compromise its structural integrity. EHMSs must withstand extreme hyperthermal environments: they must survive heat fluxes in the range from 300 up to 1 000 W cm^{-2}. The temperatures inside the rocket motor case typically reach 2 800 °C and interior pressures may exceed 100 bar. The insulator should have high elongation at break thus to absorb the mechanical stresses induced to the rocket motor during propellant casting, storage, transportation, and flight. Elastomeric HSMs also enable the possibility to integrate a movable nozzle to the engine: in fact, in order to vector the trust, the nozzle of SRMs is oriented by hydraulic or electric actuators, with the constrain to preserve the confinement of the combustion gas within the case. Among elastomeric matrices used for SRM liners, Ethylene Propylene Diene Monomer (M-class) rubber (EPDM), where the M-class indicates that the polymer backbone chain consists of methylene units, represents one of the best matrices [20] for EHSMs. The thermal stability of EPDM can be attributed to its saturated main chain structure.[21] EPDM exhibits outstanding resistance to oxidation, ozonization, and weathering effects: it also possesses excellent low temperature properties and an extraordinary long shelf life. Additionally, EPDM has the lowest density among elastomers (about 0.85 g cm^{-3}). For all these reasons, EPDM is the ideal candidate matrix for EHSMs. To date, the state of the art EHSM for SRMs is represented by EPDM filled with Aramid fibers or pulp. Aramid fibers have been incorporated in EPDM based EHMSs because of their high thermal capacity, high chemical stability, high fire resistance, low thermal conductivity, and high ablation resistance. Due to an enhanced degree of fibrillation, the use of Aramid pulp (Kevlar or Twaron) also promotes an high physical adhesion with the matrix. Accordingly, the use of Aramid pulp not only enhances the mechanical properties of the insulator but also helps to form a relatively strong char thus reducing the degradation of the virgin material. The amount of Aramid pulp typically ranges from few percentage points up to about 30%[5,22]: increasing the content of the fibrous reinforcement, the erosion rate is reduced but also the elongation at break typically decreases. Moreover, at high fiber percentages, it can be difficult to obtain an homogeneous distribution of the filaments also leading to a non-uniform ablation rate.

In light of the properties of EPDM/Aramid EHSMs, particularly, of their ability to withstand heat fluxes in the range (300–1000) W cm^{-2}, we envisioned to use an EPDM/Aramid compound to impregnate a high temperature woven fabric, thus to produce a flexible, heat resistant, elastomeric flexible composite (EFC) which would represent the baseline of the new concept of FTPS. An example of layup of the proposed EFC is reported in Figure 2c,d. In our research, because of their remarkable properties as high temperature reinforcements, carbon fibers based fabrics were selected: however, other high performance reinforcement could be used. If compared to the baseline flexible TPS tested on the IRVE-3, the solution here proposed would be able to handle heat fluxes quite larger than the requirements for the next generation FTPSs (150 W cm^{-2}). In analogy to a liner used in a SRM, this EFC would work as flexible sacrificial barrier to be applied on the fore body of an inflatable decelerator: the role of the fabric embedded in the EFC would be to work as a structural reinforcement. Since during the exposure to a severe hyperthermal environment

Table 1. Main properties of the state of the art FTPS (IRVE-3) and of the alternative concept envisioned in this research.

	Composition	Maximum heat flux	Requirements for the next generation FTPSs
Baseline of the state of the art flexible TPSs (IRVE-3)	Based on Nextel fiber fabrics	$\approx$20 W cm^{-2} [b)]	$\approx$150 W cm^{-2}
Armadillo-Like configuration flexible TPS	EPDM/Aramid and carbon fiber fabrics[a)]	$\geq$300 W cm^{-2} [c)]	

[a)]The prototype tested in this research was produced using carbon fiber fabrics. Nonetheless the use of other high temperature fibers can be considered. [b)]Maximum heat flux of the baseline FTPS (Nextel based configuration) referred to the IRVE-3 experiment. [c)]Based on the typical minimum heat flux compatible with EPDM/Aramid heat shielding materials.

EPDM/Aramid ablatively recedes, the possibility to manage a heat pulse of a given time length is strictly related to the thickness of the EHSM skin applied on the exposed face of the EFC. Accordingly, increasing the duration of the heat pulse to manage, the thickness of the required EHSM layer would increase: consequently, the main drawback of the proposed configuration could be related to a loss of flexibility of the EFC once reached a certain threshold thickness of the sandwich structure. Moreover, the minimum bending radius required to pack the EFC could also be compromised thus hindering its use as a FTPS. How to overcome the possible limitation of the proposed solution?

In order to bypass the above-mentioned limit represented by the use of an EFC in which the thermal barrier is intimately integrated with the structural component, we proposed to introduce an armadillo-like configuration (ALC) in which the main heat pulse is shielded by a series of flexible, overlapping tiles (or sloughs) made of EPDM/Aramid. This solution, which is summarized in Figure 1c, represents the second tenet of the original FTPS concept envisioned and here proposed. In vacuum of the space, once the inflatable TPS is fully deployed, each single tile would be in an open state (Figure 1c_1): there would be no overlap among tiles. When the inflatable decelerator begins to interact with the planetary atmosphere, by virtue of the shear stress produced during the re-entry flight, the tiles would be constrained to overlap one each other, thus to form a continuous barrier made of EPDM/Aramid (Figure 1c_2). The effective thickness of the resulting heat shield would be dependent on the degree of overlapping among tiles and on their geometrical dimensions: accordingly, modulating the geometries and dimensions (length and thickness) of the tiles, it would be possible to tune the effective thickness of the resulting ablative liner, and to control the lifetime of the FTPS, i.e., to manage heat pulses of different durations. It is worth to remark that the FTPS system here proposed could be integrated on existing technologies for inflatable heat shields: in fact, once faced the most severe heat pulse, the ALC-FTPS would be ablatively removed and, a traditional FTPS placed under the ALC-FTPS would be in charge to manage a second, low intensity heat flux. The main merits and benefits of the FTPS here proposed can be summarized as follows: first of all, the use of elastomeric ablatives – namely EPDM/Aramid – specifically designed to withstand severe heat fluxes (300–1000 W cm^{-2}) could enable the possibility to overcome the limits of the state of the art flexible TPS and, at the same time, to satisfy the ablation resistant requirements of next generation FTPS (150 W cm^{-2}). At the same time, the proposed Armadillo like configuration, would ensure the best exploitation of the intrinsic properties of EPDM/Aramid, without compromising the flexibility of the TPS, and the necessity to inflate and deploy the packed structure. The concept here presented of an Armadillo like FTPS based on EPDM/Aramid is original and never tested. Table 1 summarizes the main properties of the IRVE-3 baseline and of the ALC-FTPS here proposed.

2. Experimental Section

2.1. Materials

The first part of this research dealt with the necessity to produce an EPDM/Aramid compound to be used for the impregnation of the carbon woven fabric and for the production of the Armadillo-like configuration FTPS tiles. The formulation of the produced EHSM was tuned according to the state of the art compositions for this class of ablatives. The chosen EPDM was a low viscosity semicrystalline grade ethylene-propylene-diene rubber (DuPont, Nordel IP-4725P), kindly supplied by Resinex Italy. Aramid pulp (Twaron 1099) was supplied by Teijin. The amount of pulp used to compound the tested formulation was set to 10 phr since this percentage typically tends to produce the best compromise between the mechanical and ablative properties of EPDM based EHSMs.[23–29] Nanosilica particles (R7200 grade, kindly supplied by Evonik) was used to increase the ablation resistance of the material[29]: according to our experience and to the wide literature on EPDM based EHSMs, 20 phr of nanosilica resulted to be a proper amount of silica able to produce good ablative properties.[30,31] Paraffin oil (BFR 20, supplied by RA. M. OIL, Napoli-Italy) was used as a plasticizer agent. In fact, the processing of EPDM based insulators can be improved by the addition of processing aids such as aromatic or hydrocarbon oil: the use of oils reduce the viscosity, the mixing energy, and time also improving the preservation of the fibrous reinforcements. A liquid dicumyl peroxide (2,5-bis(*tert*-butylperoxy)-2-5-dimethylhexane, supplied by Sigma–Aldrich) was chosen as vulcanizing agent. The carbon fiber fabric (supplied by Angeloni, Italy) was a 0°/90° plane woven fabric with a nominal areal weight of 200 g m^{-2} and a thickness of about 0.2 mm.

2.2. Preparation of the EPDM/Aramid Compound

The EPDM based EHSMs were prepared using a single screw extruder (Bausano SD3025). First the EPDM pellets were pre-heated in an oven at 70 °C. Paraffin oil (15 phr) was then added: following, Aramid pulp (10 phr), and nanosilica (20 phr) were compounded with the EPDM. Once an homogeneous mixture was obtained the vulcanization agent (4 phr) was added.

2.3. Preparation of the Elastomeric Flexible Composite

The EPDM/Aramid compound and the carbon fabric were used to prepare an EFC. First of all, it was necessary to produce un-vulcanized disks made of EPDM/Aramid compound with a well-defined thickness. An annular mold with a thickness of 0.5 mm was used to obtain the three disks of EPDM/Aramid to be used for the impregnation of the carbon fabrics. These disks (Figure 3a) were obtained as follows: a calibrated amount of the compound was put at the center of the mold, then by means of a parallel plates heated press, a pressure of 50 bar and a temperature of 100 °C were applied for 120 s. In such a way, the elastomeric blend softened thus to take the shape of the inner part of the mold: the low processing temperature and the short time in the press prevented the vulcanization of the compound. Two disks of carbon fabric having the same dimensions of the un-vulcanized EPDM/Aramid plies were cut (Figure 3b): the EFC was produced according to the configuration reported in Figure 2c. The two carbon fabrics were stacked in order to obtain a quasi-isotropic configuration. All the stacked disks were put in an annular mold with a thickness of 2 mm

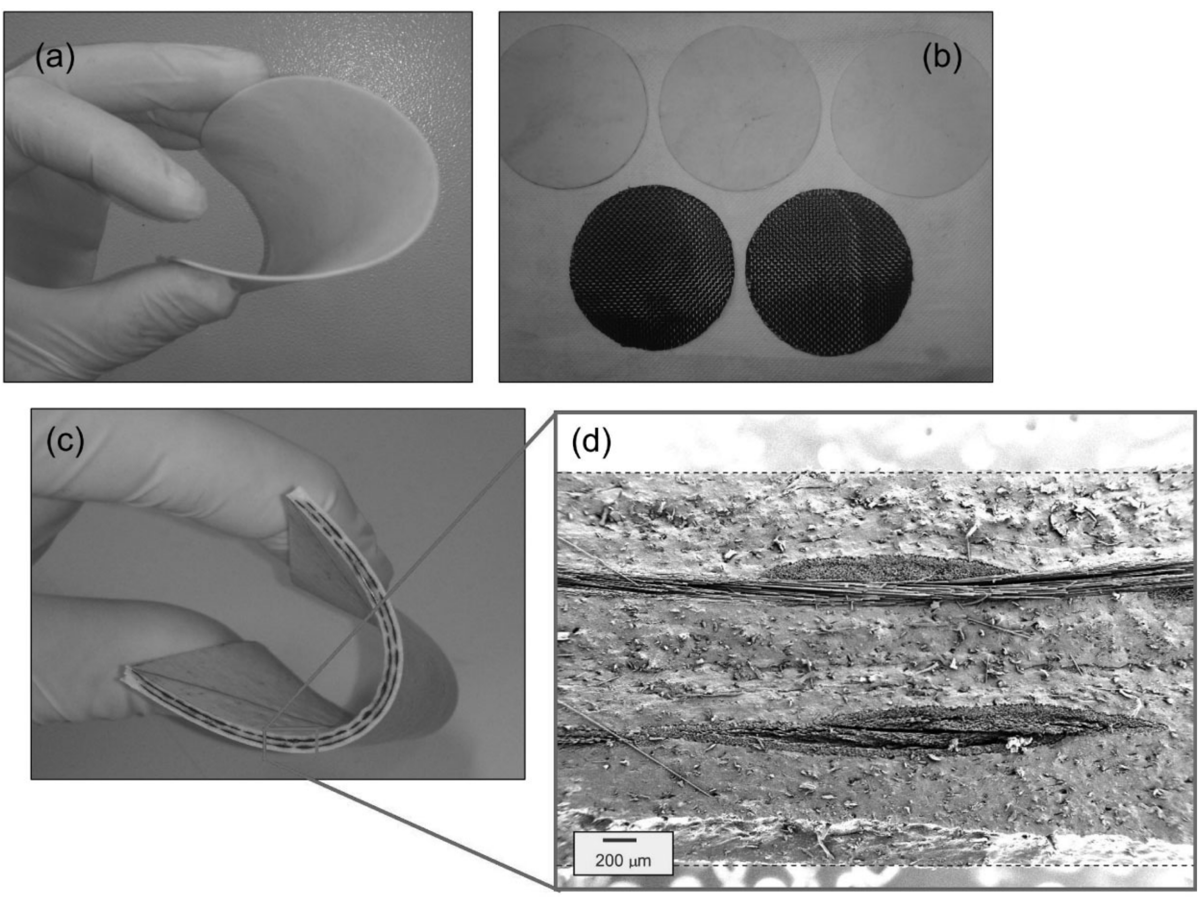

Figure 3. Appearance of an-vulcanized disk made of EPDM/Aramid compound with a well-defined thickness (a). Un-vulcanized EPDM/Aramid disks and carbon fabrics used to prepare the elastomeric flexible composite (b). Typical appearance of the fully vulcanized elastomeric flexible composite prepared according to the configuration reported in Figure 2c (c). FESEM section of the produced elastomeric flexible composite (d).

and placed in the press at a pressure of 50 bar and at a temperature of 180 °C for 2 h. The typical appearance of the fully vulcanized EFC is showed in Figure 3c. The section of the produced EFC was studied with FESEM (Figure 3d). The carbon fabric exhibited a high degree of integration in the EPDM/Aramid plies showing the effectiveness of the impregnation process. This analysis also allows to identify some roughness on the EPDM/Aramid surface, which is strictly related to the Aramid pulp domains dispersed and integrated in the matrix.

2.4. Preparation of the Armadillo-Like FTPS

A prototype of an Armadillo-like FTPS was produced starting from the EFC. The tiles to be applied on the EFC were produced using the same procedure employed to prepare the 0.5 mm thick EPDM/Aramid plies. However, the thickness of the disk prepared to produce the tiles was increased to 2 mm. Once vulcanized using the same conditions employed for the preparation of the EFC, tiles having the dimension of 35 mm by 70 mm by 2 mm were cut from the disks. The tiles were integrated on the EFC using an adhesive specifically designed to bond EDPM based components (Loxeal 32, Loxeal, Italy). It is worth to remark that we did not want to optimize the technique used to integrate the tiles on the EFC: in fact, at this stage of the research, the use of a specific adhesive for EPDM resulted to be good enough to test the new concept of FTPS. Future developments will address the best procedures to integrate the tiles on the EFC.

2.5. Relevant Characterizations

In order to evaluate the micro-morphology of the produced materials, a field emission scanning electron microscope (FESEM) Zeiss, model Supra 25 was used. Moreover, the mechanical properties of the EPDM/Aramid composite were evaluated via tensile characterization performed with a dynamometer LLOYD Instrument model LR30K, according to ASTM D412 standard. The mechanical properties of the produced EFCs were also studied.

In order to appropriately test the produced EPDM/Aramid compound used to prepare the EFC and the tiles of the final Armadillo-like structure, a facility able to produce severe hyper-thermal environment was considered. Particularly, an oxy-acetylene torch based test bed was used (Figure 4a): in fact, the most common way to perform a test, which can partially simulate the severe hyper-thermal environment is based on the use of an oxy-acetylene torch. ASTM-E-285-80[32] provides the general guidelines to arrange a test bed based on the use of an oxy-acetylene flame torch. It essentially consists of the following devices: gas vessels, pressure gauges, flux meters, and the torch were used to provide heat. The possibility of finely controlling the pressure and the gas fluxes were essential to perform any repeatable, quantitative test. A detailed description of this device can be found in Natali et al.[27] The mount used to hold the specimen is shown in Figure 4b. The flame was applied on a face of the EPDM/Aramid cubic samples along the same direction of the application of the pressure during the vulcanization of the samples (Figure 4c). In this study, the distance between the sample surface and the flame was set at

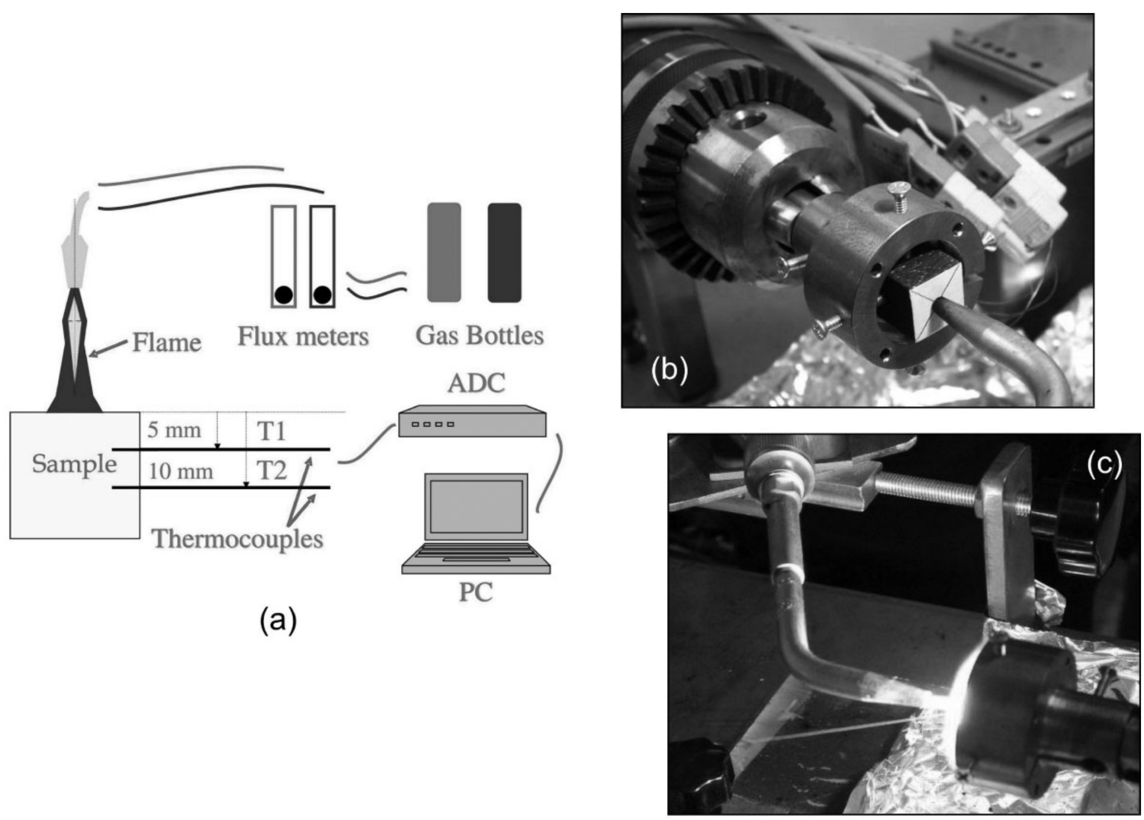

Figure 4. Oxy-acetylene torch based test bed (a). Sample holder (b). Application of the flame on a face of a characteristic cubic sample (c).

15 mm and the heat flux produced by the torch was set at 500 W cm^{-2}: the calibration of the power of the torch was carried out using a copper slug calorimeter.[27] An acetylene on oxidizer ratio equal to 1.33 was selected thus to produce a neutral flame. The in depth temperature profiles were acquired at 5 mm (referred as T1) and 10 mm (T2) from the hot surface. Thermocouples were arranged in two blind holes drilled parallel at the exposed surface of the samples. To ensure a consistent acquisition of the temperatures, the depth of the holes was kept constant at 4 mm. Fully sheathed, ungrounded, K-type thermocouples having a diameter of 0.5 mm were used. The external exposed body of the thermocouples was protected using two alumina tubes ensuring a complete protection of these sensors. All the specimens were exposed to the flame for 40 s. Five specimens were tested. The erosion rate due to the ablation process was also evaluated. The burnt surface of the samples and the section of the carbonaceous residue of the materials were analyzed by FESEM and visual inspection.

3. Results and Discussion

3.1. Oxy-Acetylene Torch Test of the EPDM/Aramid Compound

According to Figure 5a, it is possible to verify that the integration of the EPDM/Kevlar tiles on the EFC did not compromise the bending capability of the flexible substrate. Figure 5b shows the appearance of a prototype of a representative section of the deployed and un-compacted Armadillo-like FTPS: in this state, the tiles anchored on the surface of the EFC are free to move. Once a pressure is applied on the surface of the tiles, they tend to compact thus producing a continuous barrier composed of EPDM/Aramid heat shielding material (Figure 5c). The effective thickness of the resulting heat shield is dependent on the degree of overlapping among tiles and on their shape and dimension: as an example, the higher the length (and thickness) of the tiles, the higher the consequent overlap among them and the higher the effective thickness of the ablative liner. In order to estimate the pressure necessary to compress the tiles of the produced prototype, a metal cylinder with given mass and area was applied on the produced prototype as showed in Figure 5f,g. Since the cylinder had a mass equal to 50 g and a diameter of 18.5 mm, the resulting pressure applied on the tiles resulted to be equal to 0.018 atm. According to Figure 3f, this very limited pressure was able to completely compact Armadillo-like structure from the open state (Figure 5d,e) thus producing a continuous heat shield: considering the maximum measured nose cap pressures recorded during IRVE-3 re-entry (0.1 atm),[33] the pressure

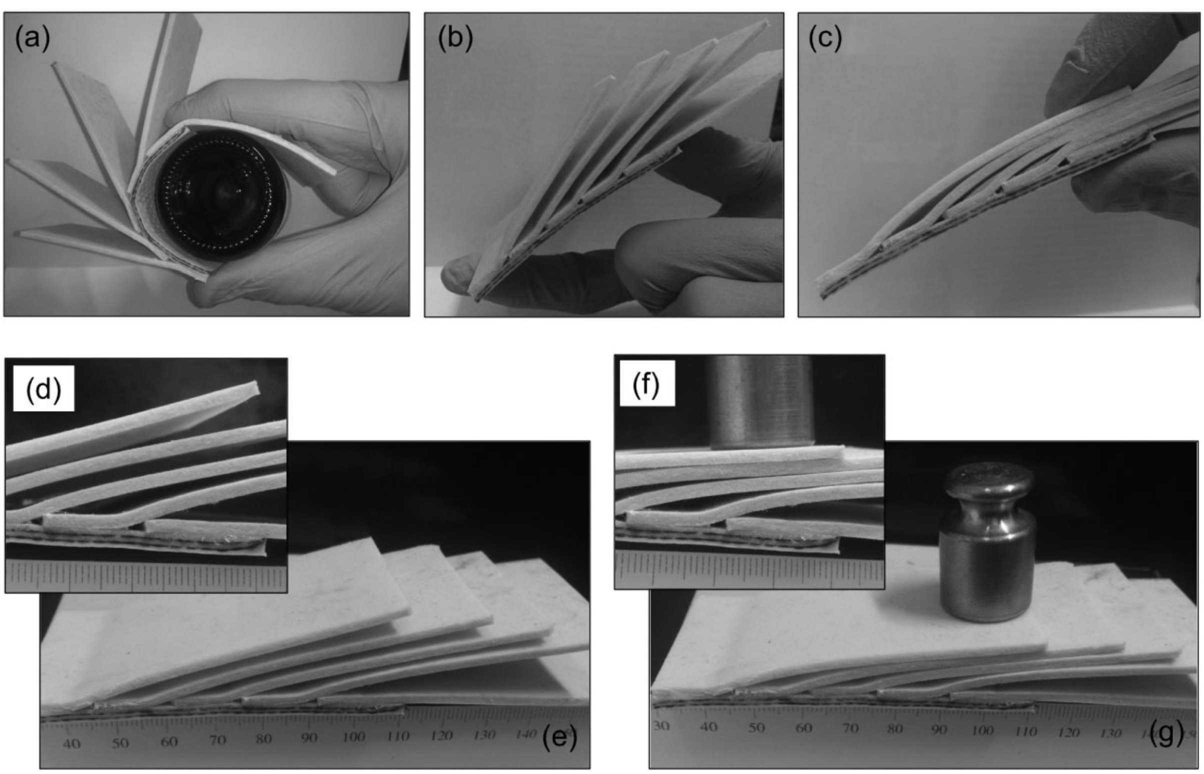

Figure 5. Evidence of the capability of the ALC-FTPS to be bent (a). Representative section of the deployed and un-compacted Armadillo-like FTPS in which the tiles anchored on the surface of the EFC are free to move (b). Once a pressure is applied on the surface of the tiles, they tend to compact thus producing a continuous barrier (c). Detail of the Armadillo-like structure in the open state (d and e). Application of a metal cylinder with a given mass and area on the produced prototype for the estimation of the pressure necessary to compress the tiles (f and g).

Table 2. Mechanical properties.

	Max.strength [MPa]	Deformation at max. strength[%]	Elastic modulus [MPa]
EPDM + Aramid pulp	6.2 ± 0.4	96.7 ± 11.4	16.0 ± 1.7
Elastomeric flexible composite	20.6 ± 1.8	10.9 ± 1.4	297.6 ± 22.1

necessary to overlap the tiles resulted to be compatible with a real flight profile for an inflatable TPS.

3.2. Mechanical Properties

The results of the tensile tests on the EPDM/Aramid compound as well as on the EFC are reported in Table 2. If compared to the EPDM/Aramid compound, the introduction of the carbon fiber fabric allowed to produce an EFC with increased elastic modulus and maximum strength.

3.3. Oxy-Acetylene Torch Test of the EPDM/Aramid Compound

Figure 6a shows a representative post burning surfaces of an EPDM/Aramid sample. The exposure to the torch plume produced a compact char with some macro fractures on the exposed surface. This is the typical response of this class of elastomeric ablatives once exposed to severe hyperthermal environment. The actual ablation efficiency of an EHSM mainly depends on the char layer of the insulator[34]: in fact, the charred region attached on the virgin material works as an heat skin and it is also responsible of the preservation of

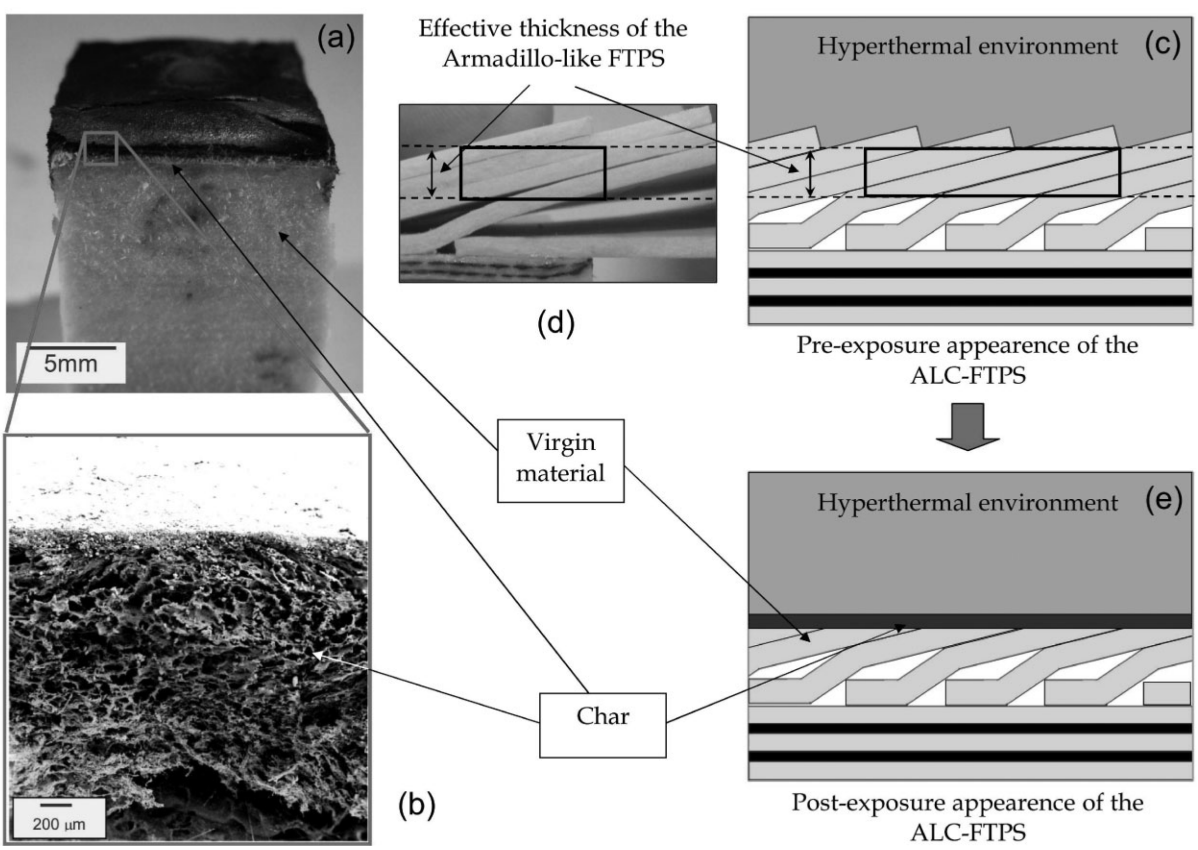

Figure 6. Post burning appearance of an EPDM/Aramid sample tested with the oxy-acetylene torch (a). Surface and section (through thickness) of the char region (b). Appearance of the compacted ALC-FTPS prior to be ablatively eroded. (c and d). Once the TPS experienced the heat pulse, the dimensions of the tiles is changed and, the effective thickness of the thermal barrier is ablatively reduced as for an equivalent bulk monolithic liner exposed to the same conditions (e).

the un-degraded material. The morphology of the burnt surfaces was also investigated by SEM analysis. Figure 6b reports the surface and the section (through thickness) of the char region. SEM analysis revealed that once turned in a carbonaceous worms, Aramid microfibers with their high degree of fibrillation, worked as a local reinforcement of the charred region.

3.4. Insulation Properties and Erosion Rate

Once the in-depth temperature profile were acquired at 5 mm (T1) and 10 mm (T2) from the exposed surface of the burnt samples, the insulation capability of the material was evaluated: as a matter of fact, EPDM/Aramid compound showed to be a very good insulating material. In fact, even after an exposure of 40 s to a severe heat flux of 500 W cm^{-2}, the maximum temperature recorded at 5 mm resulted to be equal to (168.5 ± 5.7) °C whilst the temperature recorded at 10 mm was (57.5 ± 1.8) °C. This evidence clearly confirms the effectiveness of EPDM/Kevlar to work both as an heat sink and as a thermal insulator. The measured recession rate of the ablative, which is strictly related to the amount of removed material, was of (0.090 ± 0.005) mm s^{-1}: this low erosion rate also evidenced the high erosion resistance of this class of elastomeric HSMs. In light of these results, it is possible to predict how the compacted ALC-FTPS would respond to an hyperthermal environment. Figure 6c,d shows the appearance of the compacted ALC-FTPS prior to be ablatively eroded. Once the TPS experienced the heat pulse (Figure 6e), the dimensions of the tiles would be changed and the effective thickness of the thermal barrier would be ablatively reduced as for a bulk monolithic liner exposed to the same conditions.

3.5. Testing of Armadillo-Like Configuration

To confirm the above hypothesis on the actual response of an ALC-FTPS exposed to an hyperthermal environment, a sub-scale prototype of the Armadillo-like FTPS (Figure 7a) was tested with the oxy-acetylene torch as showed in Figure 7b. The torch plume was applied thus to simulate the re-entry conditions of the fully deployed ALC-FTPS: the purpose of this test was to practically verify the ability of the compacted overlapping tiles to work as a bulk thermal barrier of a given equivalent effective thickness. The duration of heat pulse was set to 20 s. The heat flux was tangential to the tile edges and distance between the first tile and the torch tip was set to 15 mm, as for the tests

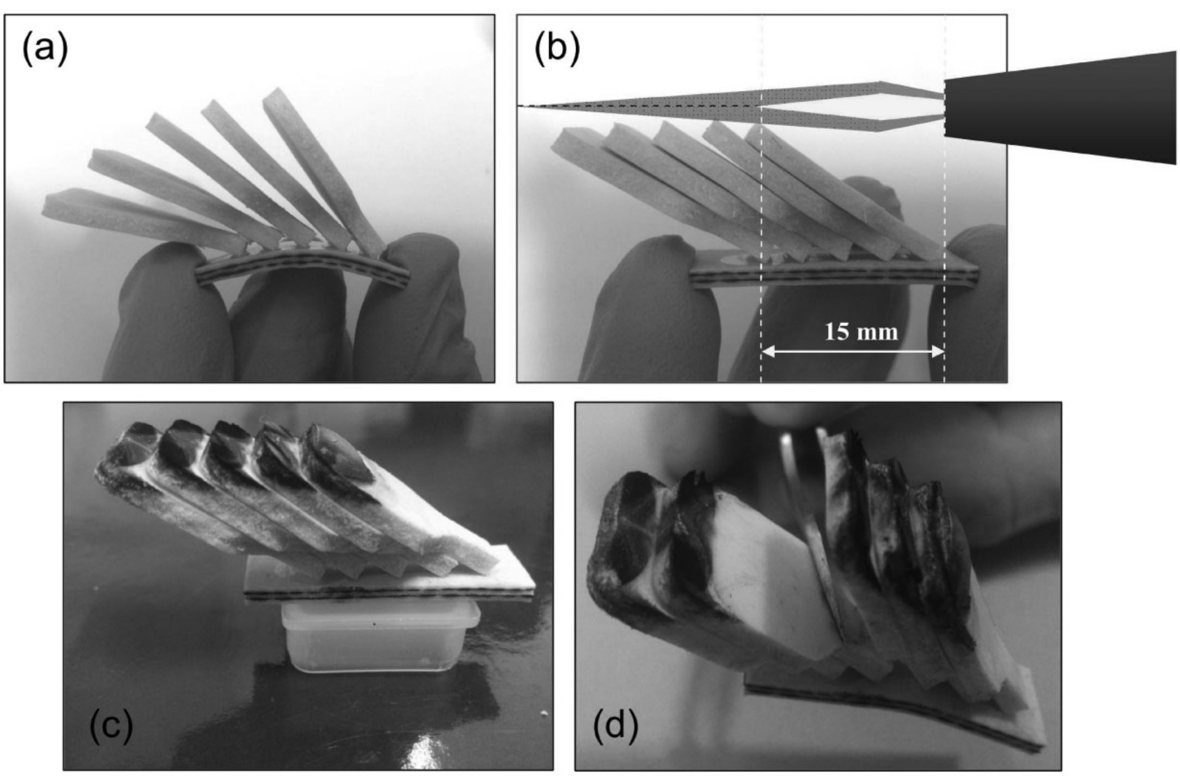

Figure 7. Sub-scale prototype of the proposed Armadillo-like FTPS prepared to be tested with an oxy-acetylene torch (a). Application of the oxy-acetylene torch on the prototype (b). Post-burning appearance of the tested sample (c) in a compacted state. Inner surfaces between two tiles: they remained preserved and unaffected by the ablation process (d).

carried out on the cubic samples: with the increase of the distance from the torch tip, the heat flux tended to decrease. However, in light of the nature and goal of this test, the non-uniformity of the resulting heat flux field did not represent a limit to the validity of the experiment. The post-burning appearance of the tested sample is showed in Figure 7c. Once tested, the state of the tiles was investigated by visual inspection: it resulted that only the part of the tiles directly exposed to the torch plume experienced charring. On the other hand, as a result of the compaction of the sloughs, the inner surfaces of tiles remained preserved and unaffected by the ablation process (Figure 7d): this evidence showed the effectiveness of the EPDM/Aramid tiles arranged in an Armadillo-like configuration, in a compacted state, to work as an equivalent monolithic thermal barrier.

4. Conclusions

In this research a new concept of flexible TPS was proposed and studied. The envisioned FTPS was based on the use of EHSMs traditionally used to produce the liners of SRMs, particularly of EPDM/Aramid compounds. In fact this class of ablatives allows to manage heat fluxes in excess of 300 W cm^{-2} thus satisfying the requirements for the next generation FTPS, which should survive heat fluxes higher than 150 W cm^{-2}. However, in order to better exploit the properties of EPDM/Aramid, we proposed to use a series a movable sacrificial tiles arranged in an Armadillo-like configuration thus to preserve the possibility to obtain a flexible and inflatable TPS. In light of the results of this research, the following conclusions can be drawn for the concept of Armadillo-like flexible TPS here introduced. First of all, the EPDM/Aramid showed to effectively impregnate a woven carbon fabric. The resulting EFC could be used as a structural substrate for a series of overlapping EPDM/Aramid tiles which, once compressed, could work as a continuous flexible thermal barrier. The degree of overlap among tiles (and their geometry and dimensions) directly influences the effective thickness of the resulting heat shield. The oxy-acetylene torch test confirmed the working principle of the proposed system. However, to fully confirm the possibility to exploit the concept here introduced of FTPS, the characterization of the proposed ALC-FTPS design via arc-jet torches must be addressed.

The experience acquired in this research also indicated some possible improvements to be applied and tested on the concept of the FTPS here introduced. Particularly:

(i) To further improve the mechanical properties of the EFC, the EPDM/Aramid baseline could be modified with the use of additional polymeric phases potentially able to increase the capability of the polymer matrix to impregnate the fabric. According to literature, commonly used EPDM based ablatives usually consist of more than one polymeric phase: in fact, with EPDM as a primary polymer base, matrices such as liquid EPDM[35,36] and adhesion promoting polymers such as hydroxy-terminated polybutadiene (HTPB)[20] have been successful used as secondary polymers. Most likely, the use of these adhesion promoters could improve the mechanical interaction between the elastomeric phase and the structural woven fabric thus to produce a flexible composite with enhanced mechanical properties. Moreover, to the same aim, the use of chemical compatibilizers could also optimize the affinity between the polymeric phase and the woven fabric. As an example, the functionalization of the EPDM matrix with maleic anhydride (MAH-g-EPDM) or, as an alternative, the use of a commercial MAH-g-EPDM, could be considered. Otherwise, the possibility to functionalize the EPDM using silanes could also represent a valid alternative.

(ii) To extend the lifetime of the EDPM based ablative compound, the use of new high performance fibers[37] having higher heat resistance than Aramid could be considered. An heat shielding material with an improved ablation resistance could extend the lifetime of the sacrificial tiles and, at the same time, could also reduce the amount of material necessary to tailor the FTPS. To support this hypothesis, very interesting results on the use of new fibers in EPDM based ablatives were obtained by several researchers. As an example, Jia et al.[31,38] replaced Aramid with polysulfonamide (PSA) fibers. According to the authors, compared to Aramid based EHSMs, the ablative properties of the PSA-pulp/EPDM blends were enhanced: the enhanced thermal stability of PSA fiber was directly related to the additional sulfone group ($-SO_2-$) in the main chain of the PSA fiber thus influencing the final properties of the EHSM. Among new generation organic fibers, poly(*p*-phenylene-2,6-benzobisoxazole) – PBO (Zylon) filaments showed to be very promising candidates when used as a replacement of Kevlar. It has been reported that the thermal stability and the carbon residue of PBO fibers under nitrogen at 1 000 °C are much higher than Aramid fiber.[33] According to Gao et al.[24] if compared to traditional EPDM/Aramid ablatives, the erosion rate as well as the loss of mass of the EPDM/Zylon was lower than 50 wt% Han et al.[25] also reported the use of polyimide (PI) short fiber-filled EPDM insulators. Compared with Aramid fibers, polyimide fibers exhibited better thermal stability and higher char residues because of their stiff aromatic backbones and aromatic imide groups of the molecular main chains.

(iii) The use of new generation, nanostructured EHSMs could also be considered. As an example, recent researches on thermoplastic polyurethane elastomer nanocomposites (TPUNs)[26] showed to be potentially able to constitute an alternative to traditional EDPM based ablatives. The processing of TPUN is quite similar to EPDM based ablatives: once processed as a laminate it could be used to impregnate a fabric as in the present research.

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