A NEW CONCEPT FOR A HYBRID TPS FOR MULTIPLE ATMOSPHERIC ENTRY PROBES: A POROUS CERAMIC REFRACTORY CONTAINING AN ABLATIVE POLYMER COMPOSITE OR OTHER PHASE-TRANSITION MATERIAL

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ABSTRACT

We present a hybrid Thermal Protection System consisting of a porous, refractory ceramic matrix filled with a polymeric fibre-reinforced composite or a solid absorbing heat by the enthalpy of the solid to liquid phase transition. In both cases the filler material acts as a heat sink. The potential advantage of such a multi-composite structure is the ability to sustain and dissipate high thermal fluxes without losing its mechanical integrity, owing to the synergistic inter-functionality of the intertwined sub-systems. Further mechanical impact resistance is provided by a porous, thermally anisotropic 2-D C/C or SiC/SiC composite layer, coated by PVD or plasma-sprayed nano-SiC and bonded onto the leading surface of the TPS.

The concept and working boundaries of such a hybrid TPS are described conceptually in this paper, with proposed materials and processing routes, based on previously developed methods and materials for other extreme applications, especially on Fusion reactor materials and HT ceramic refractory tile processing using controlled solid-state combustion (SHS).

1. INTRODUCTION

The use of ablative Thermal Protection Systems (TPS) for atmospheric entry probes has been in use since the 1960's when the technology was first developed for the Apollo missions. Since then it has changed very little, even though the problems related to its use are well known and documented (see for example [1]). The main ones are the brittleness of the charred layers after ablation, leading to loss of protective material as well as the recession of the ablator during atmospheric passage. These problems and the design and nature of an ablative TPS also means that it can only be used reliably for a single entry.

Multiple entry probes need to be able to withstand the high heat-fluxes present both at the shock-wave front and at the wake zone for at least four atmospheric entries: exit from earth's atmosphere, entry into the target planet atmosphere and the return trip. In addition, they need to be able to withstand significant micro-meteorite and other impacts, e.g. by spalling, without any loss in strength or integrity and resulting protection level for the internal systems.

Currently used ablative TPS cannot be utilized for such multi-entry missions reliably and effectively. Composite ceramic materials such as C_f/C on the other hand suffer from low toughness have higher density and as they cannot dissipate the incident heat flux, they can overheat leading to bulk failure and loss of structural integrity.

2. A HYBRID TPS CONCEPT

A new concept for multi-entry missions is obviously needed for multi-atmospheric entry missions. A possible approach is the development of a hybrid system: a heat-dissipating system (based on a material undergoing phase transition ablative or melting) encased in a refractory oxide ceramic matrix which offers containment and high temperature mechanical strength. The intertwined composite systems would act synergistically: the filler sub-system dissipates heat by a phase transition thereby reducing the heat load on the TPS while it also acts as a heat distributor within the ceramic, reducing hot spots and anisotropic thermal stresses. On the other hand, the porous ceramic refractory shields and contains the filler material. In the case of an ablative filler, its encasement in the ceramic refractory would reduce its potential for spalling, even after extensive ablation and micro fracture. In the case of a phase transition material, the porous ceramic matrix acts as a containment vehicle for the liquid formed during heating,

A graphical representation of such a system is shown in Fig. 1. The porous ceramic refractory (bottom, towards the inner surface) is filled with a phase-change material (shaded areas inside the pores). Further heat dissipation away from the hot zones and additional strength (increasing mechanical reliability) can be achieved by covering the hybrid composite system with a 2-D ceramic (SiC or C) fibre-toughened composite layer which has the advantage of very high thermal conductivity along its surface than across its thickness due to the thermal anisotropy of the ceramic fibres themselves.

For additional strength the system is finally coated by physical vapour deposition or plasma spraying with a strong and impact resistant oxide layer.

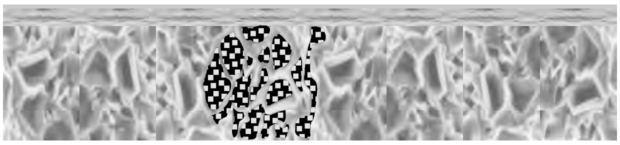

Fig. 1. Schematic representation of the proposed hybrid TPS. The porous refractory ceramic (bottom) is filled with an ablative material (shaded) and covered by a fibre-toughened ceramic (top).

Such a TPS, suitably optimised, could be expected to offer significant advantages in multi-use capability and reliability, over existing ablative or ceramic systems multiple atmospheric entries.

Each sub-system of the proposed hybrid TPS is discussed in detail below.

2.1 The porous ceramic refractory base

The porous ceramic refractory at the base of the TPS is made of a mixed oxide-spinel material made by controlled high-temperature combustion (self-propagating high-temperature synthesis – SHS). It is produced by SHS from a starting charge of MgO and Al_2O_3 (with various additives) and the final product is a hard and strong refractory with a large network of open pores. Depending on the conditions of SHS and initial charge composition, the refractory produced may have composition starting from pure Mg-Al-O spinel to almost pure sintered MgO, both very high refractoriness ceramics.

The SHS method relies on the judicious choice of initial powder charge and conditions to produce an exothermic reaction which can reach very high combustion temperatures (in this case upwards of 2500 ^oC) and thus complete reactions that, under normal conditions can take many hours. The whole process lasts just a few seconds and it is able to produce nett shapes fairly easily, including curved tiles necessary for a probe TPS. The production of porous structures such as used in the above refractory is achieved quickly and easily.

A schematic diagram of the SHS process is shown in Fig. 2. Initiation of the powder charge (in this case compacted in a cylindrical shape) is achieved by an electrical discharge and combustion wave propagates from top to bottom, leaving behind the final product.

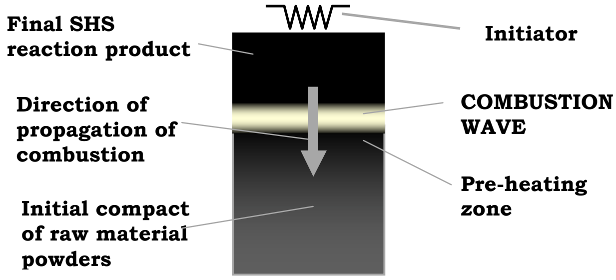

Fig. 2. Schematic of the SHS controlled combustion synthesis process for the production of the porous ceramic refractory.

Depending on the processing conditions, the SHS process can produce low or high porosity materials of many different types. The extremely fast rates of heating and cooling allow the synthesis of metastable and heavily deformed atomic structures with excellent catalytic properties.

To avoid oxidation during atmospheric entry, the refractory must already be a stable oxide. Magnesia (MgO), spinel ($MgAl_2O_4$) and alumina (Al_2O_3) are all extremely stable ceramic refractories with very good physical and mechanical characteristics for high temperature applications. Previous work [2-5] showed that a mixed structure of spinel and magnesia made by SHS offers very useful thermal properties for a thermal protection application as shown in Table 1. In fact, the materials are generally used as thermal barriers for high temperature applications in furnaces, kilns etc. In particular, the low density and high refractoriness are well suited for space TPS applications.

Table 1. Range of properties displayed by SHS spinel-magnesia mixed refractories.

PROPERTY	RANGE
Density, g/cm^3	0.5 – 1.4
Total Porosity, %	85 – 60
Compressive Strength, MPa	2 – 18

Nett Thermal Conductivity, W/Km	1.12 – 1.87
Initial softening temperature, °C	2200 – 2700
Refractoriness, °C	1900 - 2300
Thermal Heat Capacity, J/kgK	600 – 2000
Thermal Expansion Coefficient, $^oC^{-1}$ (in the range 30-1250 °C)	$1.2x10^{-5}$- $9.7x\ 10^{-6}$

By the use of SHS, the degree and morphology of porosity can be controlled by changes in both the processing conditions and the composition of the powder charge. Similarly, the mechanical strength of the resulting porous material can be increased by optimising the shape and morphology of the pores and the degree of sintering of the material. For the proposed TPS application, an open network of relatively large porosity is suggested, into which the filler material can be incorporated in a secondary operation.

2.2 The filler material.

The refractory base made of the above SHS spinel/MgO will offer good mechanical support and thermal insulation up to about 1900 °C but, to keep the temperature below this level, a heat sink material is required. It is proposed to fill the porous ceramic base with either a reinforced polymeric ablator or another solid material that would dissipate heat by the enthalpy of a phase transition. The use of such a filler material absorbing heat acts synergistically with the ceramic: the filler dissipates heat during the phase transition keeping the ceramic from overheating and the ceramic shields and mechanically contains and protects the ablator or other filler from spalling, leaking or damage.

Preliminary studies carried out already showed that it is possible to fill the porous ceramic with a range of polymeric materials containing a network of chopped SiC fibres. The final overall density of the filled ceramic was measured to be in the region of $1.5g/cm^3$. Recently, some experiments with filling the porous ceramic with a metallic salt (such as sodium metaborate which melts at about 960°C and has a relatively high enthalpy of fusion) were also successful. It is expected that such fillers could act as heat sinks by absorbing the thermal load during transition from solid to liquid, keeping the temperature of the TPS constant during the transition. The main potential problem here would be to ensure proper containment by the porous ceramic and chemical and thermal expansion compatibility with it.

2.3. The fibre-toughened CMC top layer

Although the filled porous ceramic refractory may be designed to dissipate the thermal load, it does not offer sufficient impact strength required to withstand micrometeorite or droplet impact or other mechanical loads. In fact, the refractory ceramic is brittle and therefore requires a protective top layer. For this reason it is proposed to bond on it a fibre-toughened ceramic matrix composite (CMC) layer: C/C or SiC/SiC being the most well studied. In order to take advantage of the anisotropy in thermal conductivity of the ceramic fibres (up to 40 times better conductivity along the fibres than across their thickness), a 2-D morphology of the CMC would encourage heat conductivity towards the periphery of the TPS, dissipating into the surroundings.

Bonding of the CMC layer to the refractory base can be successfully achieved by SHS [6] whereas an intermediate layer is used with good overall properties.

Finally, the CMC would need to be coated with an impervious coating, ideally of nano structure for optimum properties, that can be achieved by plasma spraying or physical vapour deposition or electro-phoretic deposition.

3. CONCLUSIONS

The hybrid system described above addresses all the main drawbacks of both the ablative and ceramic TPS used at present. Once developed and optimised for a particular application, it has the potential to offer significant benefits and advantages over existing systems enabling multiple atmospheric entry use:

- Good thermal insulation by the use of a porous high-temperature ceramic
- Sufficient heat absorption by the contained ablative or phase-transition material
- Significantly reduced possibility of damage or loss of material by vibration or during flight
- Very high impact strength against droplets or micrometeorites
- Relatively low cost and
- Ease of production and installation

4. REFERENCES

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