Making Fast Even Faster: The Use of Ultra-High Temperature Ceramics and Carbon-Carbon Composites in Hypersonic Flight

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New Speeds, New Problems

A new material is needed to withstand the extreme environment that hypersonic flight creates. This material is created by combining an ultra-high temperature ceramic (UHTC) with a carbon composite to create a protective shell able to withstand the wind, high speeds, and increased temperatures experienced during hypersonic flight.

Potentially, this material could improve many different forms of flight and make travel easier and faster for the average person. It allows planes to travel at faster speeds, enabling people to travel farther than ever before in a day and spend less time en route to their destination. It decreases the amount of time it takes to transport cargo, especially in situations where time is vital such as medical emergencies or natural disaster relief. The use of UHTCs with carbon-carbon composites has the potential to increase the speed of aircraft resulting in decreased flight time and greater connectivity of people.

Hypersonic Flight: Flight reaching speeds above Mach 5 (approx. 4000 mph)

Carbon-carbon composites

Carbon-carbon composites consist of carbon fibers that are arranged, usually through weaving, to form a matrix, such as the triaxle weave. This arrangement contributes to the strength of carbon-carbon composites.

Properties of carbon-carbon composites which make them a good candidate for use in the coating of hypersonic vehicles include high thermal conductivity, low thermal expansion, and low density. One of the most important properties of carbon-carbon composites is their resistance to high temperatures up to 1000 degrees Celsius.

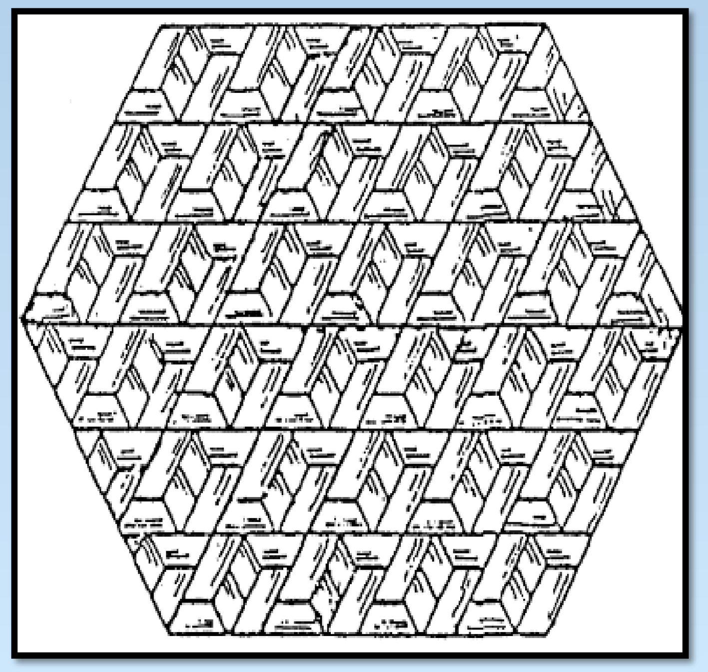
One issue with using carbon-carbon composites as a coating for hypersonic vehicles is their lack of oxidation resistance at high temperatures. This weakens the material as carbon atoms react with oxygen, ultimately decreasing its strength and cohesiveness by affecting the fiber-matrix structure of the material making it unusable as the only material in the coating of a hypersonic vehicle.

Ultra-High Temperature Ceramics

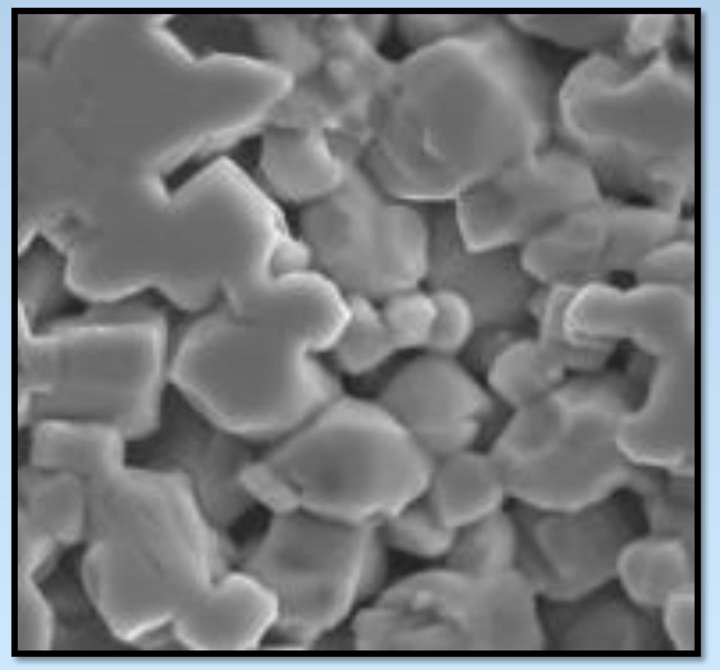
Ultra-high temperature ceramics (UHTCs) are a prime candidate for hypersonic flight because they meet the thermal requirements and are easily moldable. Due to their unique manufacturing process of sintering (hot pressing powdered UHTC into a mold), UHTCs can be shaped for a more precise fitting around more cumbersome shapes such as cones or acute angles, which are common in hypersonic vehicles, because acute angles reduce drag.

The main characteristics UHTCs possess that make them highly sought after for their use in hypersonic flight are their high melting point, high oxidation resistance, hardness, and high thermal conductivity. These properties are essential to resisting damage caused by the environment created during flight at hypersonic speeds.

Despite all of their amazing properties, UHTCs become brittle at high speeds. This predisposes them to cracking, causing them to be unsuitable when used alone as the exterior coating of a hypersonic vehicle.



The triaxle woven carbon matrix (left) versus the porous structure of Zirconium Diboride ($ZrBr_2$) (right), a common UHTC. The structural differences in these materials allow the UHTC to be interlaced into the carbon matrix. The new material created in through this process is perfect for use as a coating on hypersonic vehicles.



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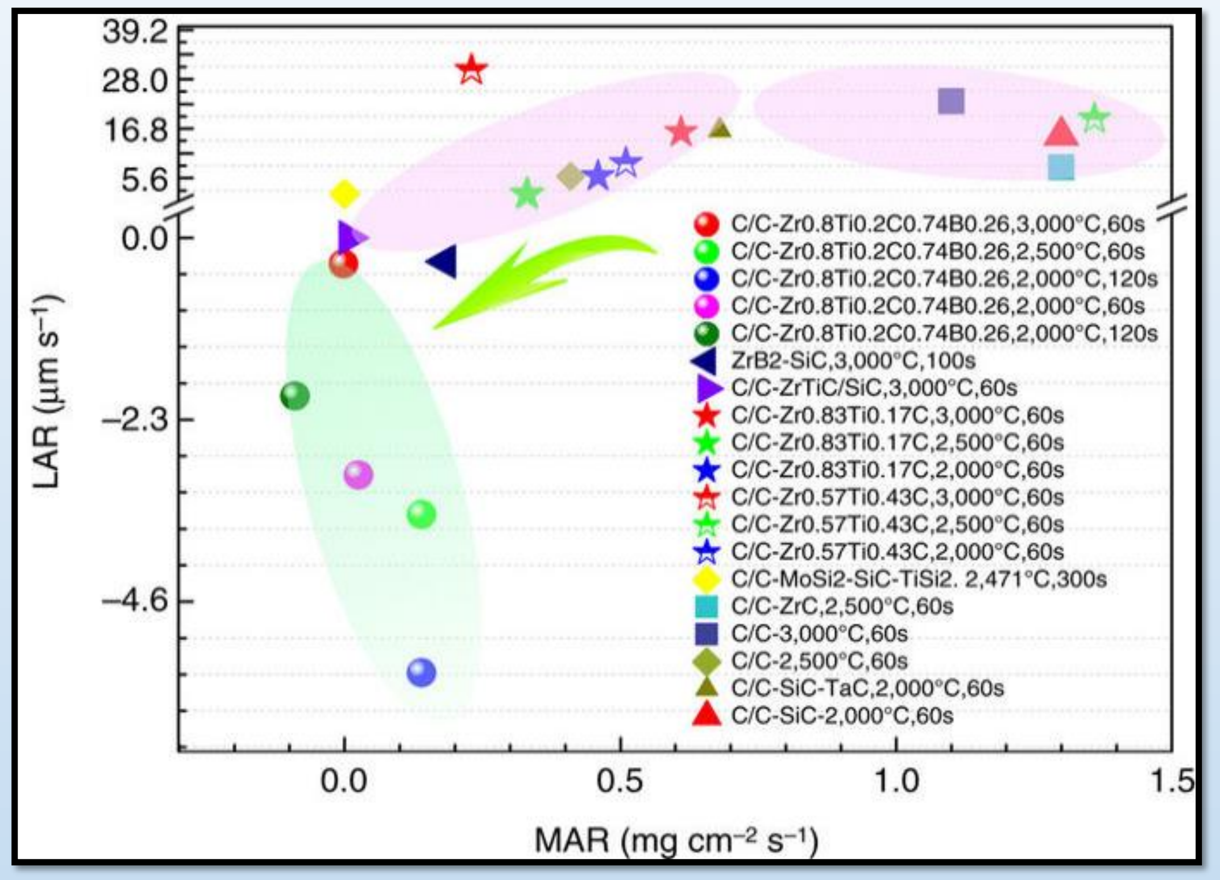
How two wrongs make a right



The ablation resistance of $Zr_{0.8}Ti_{0.2}C_{0.74}B_{0.26}$ in comparison to the zirconium diboride and the zirconium carbide. In the figure, the mass ablation rate (MAR) is compared to the linear ablation rate (LAR).

When carbon-carbon composites and UHTCs are interlaced, their individual flaws are diminished. The resulting material does not crack or oxidize at hypersonic speeds, unlike its component materials. The unique aspect of the new material is that it still exhibits the positive properties of its components such as low thermal expansion and high ablation resistance (ability to withstand extremely high temperatures). The new material also exhibits improved toughness as the UHTCs permeate and reinforce the carbon fibers.

The combination of carbon-carbon composites and UHTCs creates a coating with the potential to stand up to high speeds, harsh environments, and longevity of space travel, prolonging the life and safety of the spacecraft. This combination material is key in changing the way people travel both on and off Earth.