How can the strength of UHTCs be increased by 10% by using Silicon Carbide fibers, microcracking, and other means?

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Abstract

Due to the nature of hypersonic flow, it is difficult for many materials to withstand the extreme conditions at these speeds. Even UHTCs, a material used in hypersonic craft for its high thermal stability and strength, still present many problems, including brittleness and a lack of reusability. Solving these issues will allow hypersonic crafts to be closer to commercial viability and long term use. Our research aims to determine how we can improve the strength of UHTCs by 10% through Silicon Carbide fibers, microcracking, and other means. This is a goal within reason, but also provides enough of a benefit to be useful.

Introduction and Thesis Statement

For a hypersonic vehicle to be viable, it must be able to withstand the extreme conditions present during hypersonic flight. Some of these include temperatures ranging from 3000-5000 ℉, oxidation, and shock waves. UHTCs are currently the best material for this job. They have melting points above 5000 ℉ and have high compression resistance to withstand high speed impacts from air flow and shock waves.

However, multiple studies [1] have indicated that UHTCs are lacking in some critical categories. At temperatures above 2000 ℉, UHTCs begin to degrade. Repeated heating of the material causes cracking in the structure that grows larger and larger after each use, until the material is rendered useless. This problem is due to UHTCs' lack of thermal shock resistance. Rapid heating of the material causes it to expand and crack. Since ceramics are not crack resistant, a few cracks can cause total failure of the material.

There are some methods of minimizing these weaknesses. One of them being placing fibers, such as SiC, in the matrix in varying structures: unidirectional, laminate, chopped, and particulate fibers. The fibers are able to strengthen the UHTC against tensile forces, thus mitigating cracking, but the fibers are susceptible to oxidation. Once a crack forms in the matrix, oxygen can enter and attack the fibers. It can corrode along the entire length of the fiber, weakening the UHTC and making it more susceptible to oxidation, cracking, and thermal stresses.

Our research aims to use varying methods to improve the strength of UHTCs by at least 10%. These methods will include altering the composition of the ceramic matrix, using particulate fibers instead of linear fibers, and more. We will use [insert program name] to test the thermal shock resistance and crack resistance,.

This research paper will go through the processes we used to create the UHTCs. Then, it will focus on how we identified the effectiveness and what it will ultimately mean for hypersonic aircraft. This paper will determine if there is a way to improve the current UHTCs in an attempt to progress hypersonic flight to more commercial viability.

Section 1: Definitions & Literature

Hypersonic conditions

For our research, we need to clearly define what hypersonic conditions are as these are the conditions we will be subjecting UHTCs to. [2] Although it is not entirely accurate, it is generally thought that hypersonic conditions are achieved upon reaching mach 5. It is around this speed where the conditions of flow begin to change.

Hypersonic Flow - there are many components of hypersonic flow that make using traditional materials for aircraft impossible. It is important to understand the nature of hypersonic flow as it will determine how we design and structure the materials on hypersonic aircrafts.

Shock Waves - The sudden redirection of the flow due to the aircraft's movement. It is through shock waves that many of the components that are discussed below come to be. This also leads to force being placed on the front of a hypersonic aircraft. The nose must be able to withstand the force of the shockwave.

Temperature - hypersonic flow at 1 atm reaches a temperature range of 3000-5000 ℉ (1649-2760℃) due to the friction with the air and the fast moving aircraft. Most metals will melt at these temperatures, one exception being tungsten.

Ionization and Oxidation - due to the high temperatures in the air in hypersonic conditions, particles will begin to ionize. [2] (Fundamentals of Hypersonic Flow) These conditions take place at 1 atm. Oxygen will begin to dissociate at 3140℉ and finish at 6740℉. Nitrogen will begin to dissociate 6740℉ and finish at 15740℉. This means that ions will freely interact with the exterior of a hypersonic aircraft, leading to the corrosion of the material. Thus, oxygen and water can enter into the material and cause more corrosion, leading to the total failure of the material.

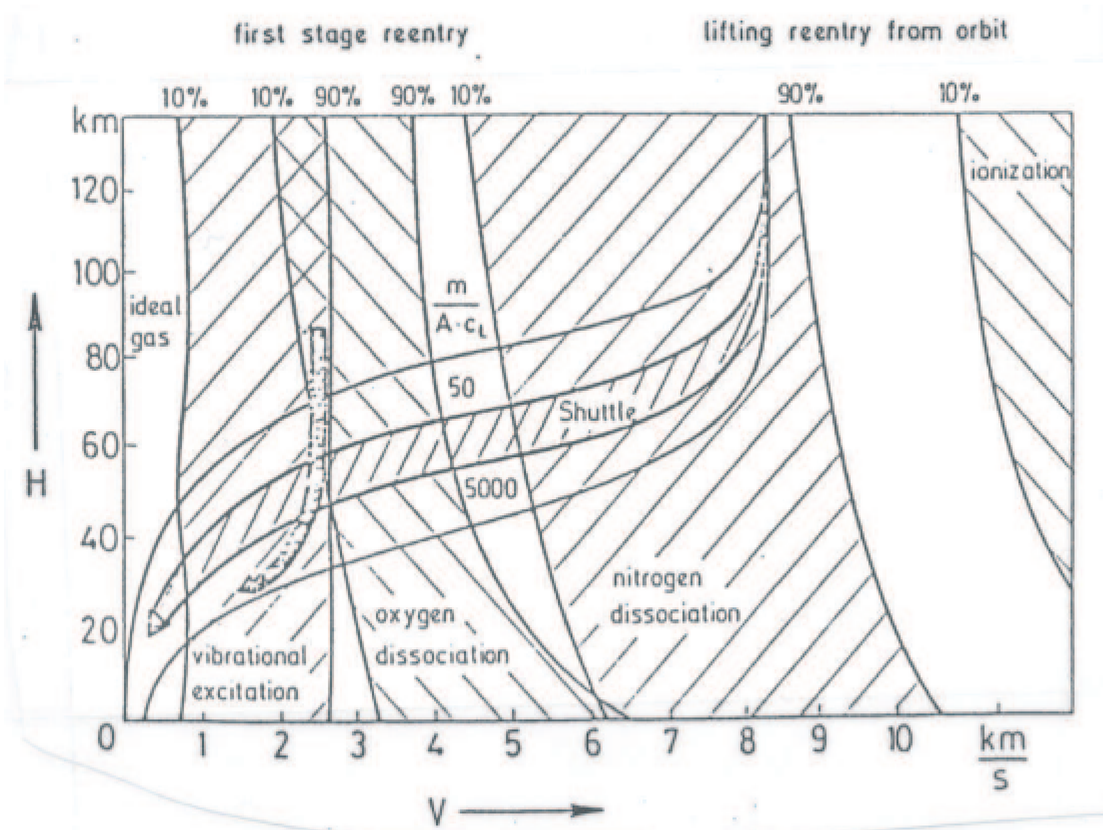

Fig. 1.1 - Map of hypersonic flight regimes (velocity on the x-axis, height in atmosphere on the y-axis). [2]

UHTCs Properties

It is these conditions that UHTCs and UHTCMCs need to survive in. However, there are also many terms that need to be defined to describe the structure, limitations, and more for UHTCs.

Thermal Shock - this is the sudden change in temperature of a material. When a material is heated this quickly, especially ceramics, it will likely crack because of the expansion. Ceramics are designed to withstand pressing force, not pulling forces. Thermal shocks can cause significant damage to the material, even leading to complete failure.

Fibers within the Matrices - there are multiple kinds of fibers that have distinct benefits for the matrix. In general, the fibers serve to aid the ceramic while it is under tension, specifically during thermal shocks.

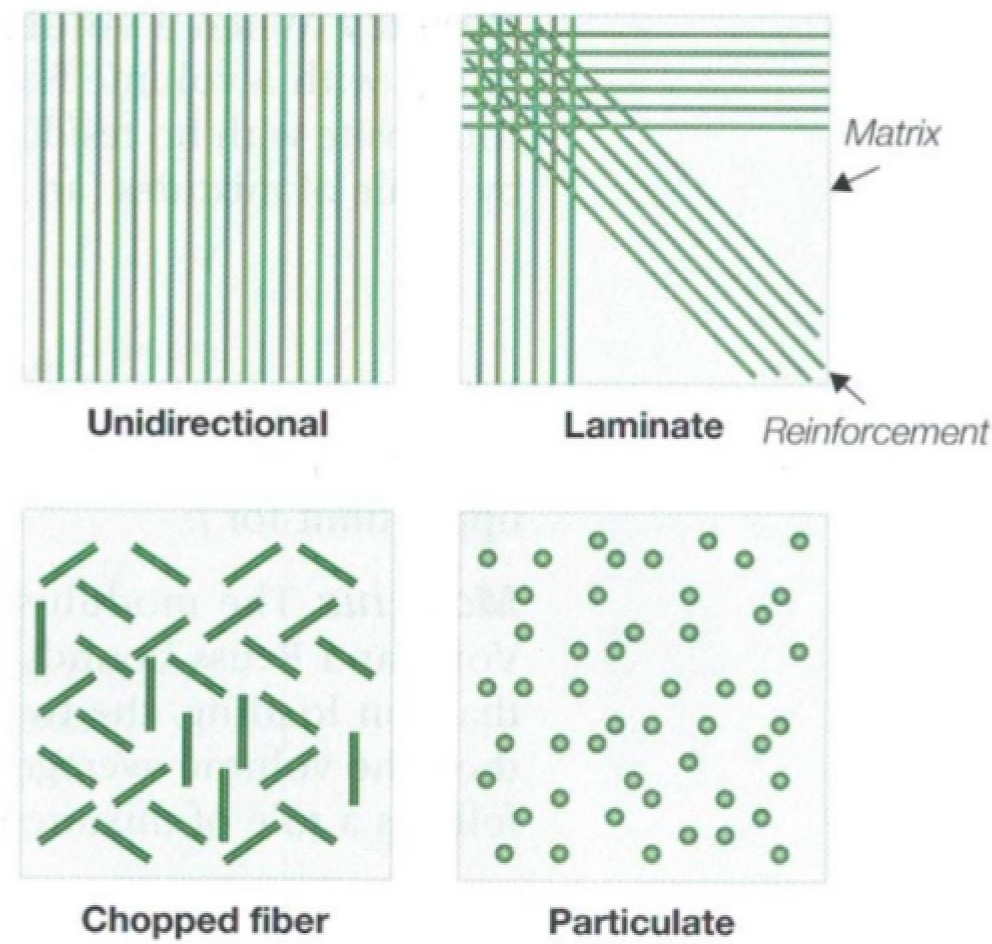

Fig. 1.2 showcases various fiber structures that can be used in ceramic composites [3]

Fig. 1.2 depicts the 4 main variations of fibers. Unidirectional and laminate are similar, only they are arranged differently in terms of planes. Our main focus will be on chopped fiber and particulate. The reason is because they lack the issues of unidirectional and laminate - one directional crack resistance and delamination.

Since unidirectional and laminate face a single direction, any crack that is able to travel parallel to the fibers will ultimately cause a complete failure of the material. This is coupled with the fact that it is unable to withstand tension in multiple directions. Chopped fibers and particulate fibers overcome this problem because of the multi directional crack resistance.

[4] An additional issue with unilateral fibers is delamination.

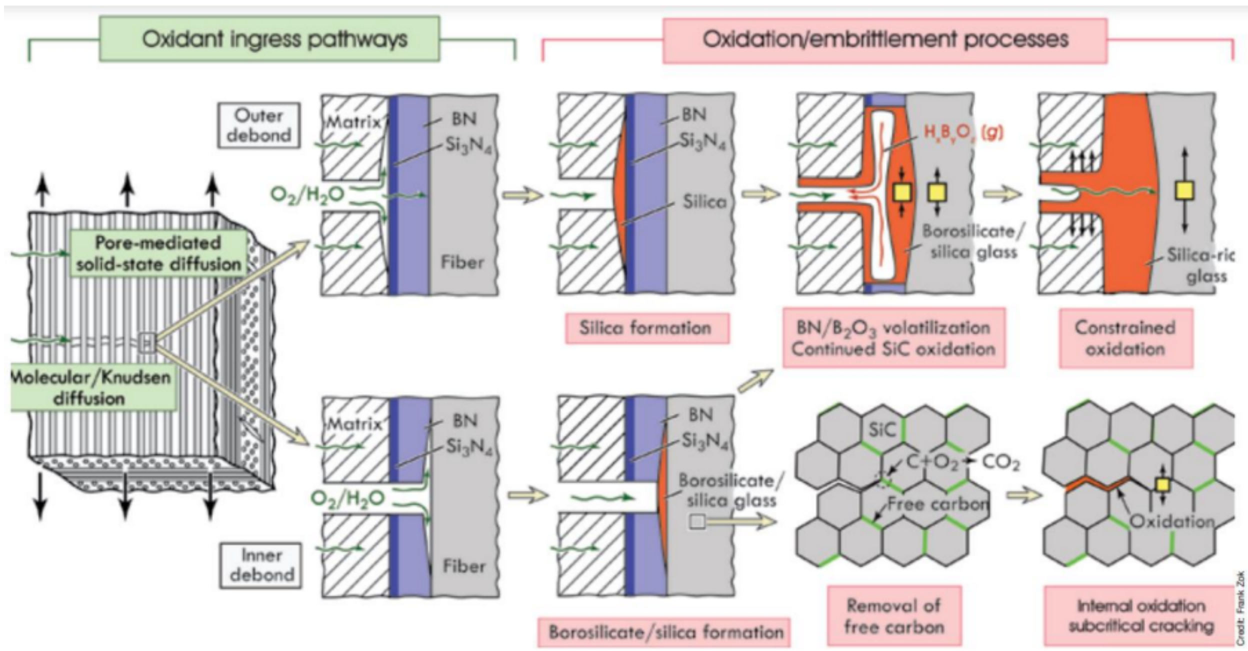

Fig. 1.3 demonstrates the delamination process for unidirectional fibers. [3]

Cracks in the matrix will allow oxygen to corrode the areas around the fiber, weakening the fibers connection to the matrix. The fiber will loosen and be unable to oppose tension on the entire material. Particulate fibers, on the other hand, will pull on cracks in order to close them.

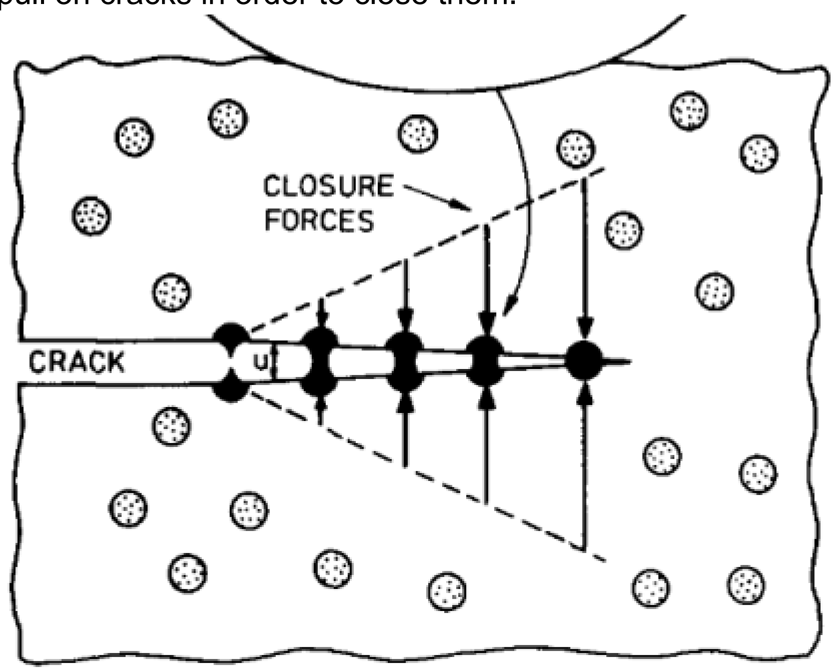

Fig. 1.4 demonstrates how particulate fibers are able to close cracks in ceramic composites by applying a closure force [4]

Importance of this Paper

This paper will be looking at research to improve the strength of UHTCs through multiple methods that combine UHTCs and UHTCMCs. This is currently a hole in the current research in this field. There is much research on the properties of UHTCs and UHTCMCs, but nothing on a material that combines and changes their properties.

UHTCs by themselves lack the fracture resistance to be completely viable for long term use. After a few flights, cracks in the matrix can overcome the maximum crack length and lead to the failure of the material. Additionally, the minimal thermal flux resistance exacerbates these problems. [5]

UHTCMCs overcome these issues with silicon-based fibers [3]. However, the unilateral fibers can not overcome cracking through erosion. Once air begins to corrode the material around the fibers, the fibers will become delaminated and become useless in preventing thermal flux expansion of the material [3]. Particulate and chopped fibers are useful in preventing corrosion issues, [3] so that is why we will investigate their potential use in matrix composites.

Section 2: Overview

The composite that we will be creating uses a SiN matrix and Si_3N_4 particulate and chopped fibers. The edges of the matrix will use chopped fibers and there will be more particulate fibers moving towards the center. Using the properties of SiN and Si_3N_4 we will determine the strength of the material, which will then be used to determine other properties (ex. Thermal resistance, etc.).

With the experimental nature of this material, there are no computational means to determine the exact properties of the material. Therefore, we will need to make one important assumption before carrying out calculations: There is a distinct separation between portions of the material containing particulate and chopped fibers. In reality, the UHTC would have a gradient between particulate and chopped fibers; however, calculating the strength of this gradient would be very difficult. Keeping the areas distinct allows us to calculate separate properties that can be experimentally tested later.

Using this assumption, [3] we can determine the young's modulus for the regions of the composite using these equations:

$$Upper\ Bound:\ E_u = fE_r + (1-f)E_m$$

$$Lower\ Bound:\ E_L = \frac{E_m E_r}{f_r E_r + (1-f)E_m}$$

E_m - young's modulus of the matrix
E_r - young's modulus of the fibers
f - volume fraction of the fibers

We will use calculated values for the young's modulus. We will assume that the volume fraction for particulates is 0.4 and that it is 0.7 for chopped fibers because particulate fibers take up a smaller volume fraction of the material. Through these equations, we can determine the upper and lower bounds for the strength of the composite's regions.

Once strength is determined, we can use these values to find other properties. One of these properties is thermal shock [11].

$$R_T = \frac{k\sigma_T(1-v)}{\alpha E}$$

σ_T - thermal stress
α - coefficient of thermal expansion
E - young's modulus
v - poisson's ratio
k = 1

With these properties, we will be able to compare this UHTC with other ones, such as Silicon Carbide. We can determine how well the created UHTC will withstand sudden heating that can be seen in hypersonic conditions. With a good thermal shock resistance, the UHTC can be applied to aircraft with little risk of cracking due to extreme heating in a short duration of time.

The final variable we will calculate is the impact resistance. Young's modulus is useful for determining how the UHTC will react to gradual tension on the material, whereas impact resistance will tell us about the material's resistance to almost instantaneous tension.

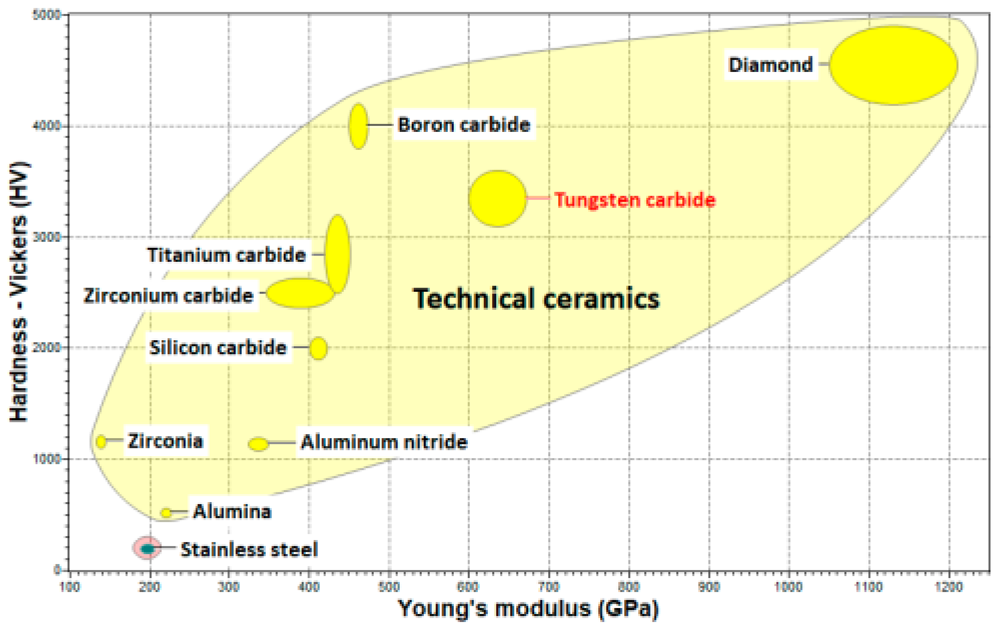

Fig. 2.1 shows an ashby chart that is used to determine the line of best fit to calculate hardness (Hv) based on Young's Modulus (GPa)

Using this ashby chart in figure 2.1, we will find the line of best fit using the least means squared type fit. For the linear equation, the x-axis will be Young's Modulus (E) and y-axs will be Impact Resistance (HV). Using the predetermined young's modulus for the UHTC, we will determine the range of impact resistances for the material. By plotting the area the ceramic falls under, we can compare its impact resistance to other materials.

The plan to create this material would be using gas vapor deposition. [15] This method would place Silicon Nitride in a chamber to be heated up. The pressure around the material would be decreased, which would eventually cause the material to vaporize. Then, we would set up the fibers in an arrangement that would provide the best distribution and strength for the material. This would likely involve placing chopped fibers near the edges of the outline of the material, aligned outwards, and placing particulate fibers spread throughout the middle portion of the outline. The Silicon Nitride gas would be sprayed over the outline and solidify, forming the ceramic matrix and creating a silicon nitride ceramic with silicon carbide fibers.

Section 3: Evidence

To begin, we first calculated the young's modulus for the particulate and chopped fiber structures, which includes both the upper and lower bounds for strength. We will assume that the volume fraction for particulate is 0.4 and chopped fiber is 0.7. [8] [9] The strength of the Si_3N_4 matrix is 165 GPa and the strength of the SiN fibers is 230 GPa at 1400℃. [14] [16] The strength of the Si_3N_4 matrix is 250 GPa and the strength of the SiN fibers is 260 GPa at 25℃. The strength for SiN is the lower bound based [8] in order to be conservative in our calculations.

Using these values, we used these equations:

$$Upper\ Bound:\ E_u = fE_r + (1 - f)E_m$$

$$Lower\ Bound:\ E_L = \frac{E_m E_r}{f_r E_r + (1-f)E_m}$$

At 1400℃

Type of Fiber	Young's Modulus Upper Bound (GPa)	Young's Modulus Lower Bound (GPa)
Particulate	204	186.03
Chopped Fiber	210.5	180.3

Fig. 3.1 shows calculated young's modulus values for both types of fibers for upper and lower bounds at 1400℃

At 25℃

Type of Fiber	Young's Modulus Upper Bound (GPa)	Young's Modulus Lower Bound (GPa)
Particulate	256	253.91
Chopped Fiber	257	252.92

Fig. 3.2 shows calculated young's modulus values for both types of fibers for upper and lower bounds at 25℃

$$R_T = \frac{k\sigma_T(1 - v)}{\alpha E}$$

Afterwards, we calculated thermal shock resistance. The thermal stress was determined by multiplying the yield of silicon nitride by ⅔. This is done to be both conservative in the design and ensure that the material is not immediately used at the maximum yield strength during an operation. The yield was 525 MPa [12], giving a thermal stress of 350 MPa. The coefficient of thermal expansion ranges from 1.4 to 3.3 10^{-6}/K [12]. We will be using the smaller value to be conservative in our approximations for the properties of this UHTC. The poisson's ratio is 0.2 [12]. For the young's modulus, we will be using the upper and lower bounds for both particulate and chopped fibers to get a range of the materials possible thermal shock resistance based on the variety of strengths.

At 1400℃

Type of Fiber	Thermal Shock Resistance Upper Bound (kw/m)	Thermal Shock Resistance Lower Bound (kw/m)
Particulate	0.98	1.08
Chopped	0.95	1.11

Fig. 3.3 shows calculated values for Thermal Shock Resistance for both types of fibers for upper and lower bounds at 1400℃

At 25℃

Type of Fiber	Thermal Shock Resistance Upper Bound (kw/m)	Thermal Shock Resistance Lower Bound (kw/m)
Particulate	0.78	0.79
Chopped	0.78	0.79

Fig. 3.4 shows calculated values for Thermal Shock Resistance for both types of fibers for upper and lower bounds at 25℃

Lastly, we found the impact resistance of the material by using the ashby chart and using the least means squared type fit to find the linear regression equation. Note that the values for diamond were excluded from the calculation. This is due to the fact that the structure of diamond is different from the structure of the ceramics in the ashby diagram. The Carbon - Carbon bonds have very different properties from the other covalent bonds in the ceramics, which meant that we did not consider it in the least mean squared type fit calculations.

The equation we found was y (Hv) = 3.75x (E) + 250. After substituting the upper and lower bound Young's Modulus for both the particulate and chopped fiber sections, the upper and lower bound values for particulate fibers, respectively, were 1015 Hv and 947.61 Hv. For chopped fibers, the upper and lower bound values were 1039.38 Hv and 926.13, respectively.

At 1400℃

Type of Fiber	Impact Resistance Upper Bound (Hv)	Impact Resistance Lower Bound (Hv)
Particulate	1015	947.61
Chopped	1039.38	926.13

Fig. 3.5 shows calculated values for Impact Resistance for both types of fibers for upper and lower bounds at 1400℃

At 25℃

Type of Fiber	Impact Resistance Upper Bound (Hv)	Impact Resistance Lower Bound (Hv)
Particulate	1210	1202.16
Chopped	1213.75	1198.45

Fig. 3.6 shows calculated values for Thermal Shock Resistance for both types of fibers for upper and lower bounds at 25℃

Section 4: Alternative Perspectives

To determine how useful the calculated UHTC is and where it can be applied, we first will compare it at two different temperatures. We have data for both 25℃ and 1400℃. By looking at how Young's Modulus, Thermal Shock Resistance, and Impact Resistance change based on temperature, we will see how well the UHTC will theoretically maintain its properties after heating.

Properties	Theoretical UHTC (particulate) at 1400℃	Theoretical UHTC (particulate) at 25℃	Percentage Difference
Young's Modulus (GPa)	186.03	253.91	-26.73%
Thermal Shock Resistance (kw/m)	1.08	0.79	+36.71%
Impact Resistance (Hv)	947.61	1202.16	-21.17%

Fig. 4.1 shows the comparisons between the UHTC at 1400℃ and 25℃ for particulate fibers. The overall change for the properties is represented by the percentage column.

Properties	Theoretical UHTC (chopped) at 1400℃	Theoretical UHTC (chopped) at 25℃	Percentage Difference
Young's Modulus (GPa)	180.3	252.92	-28.71%
Thermal Shock	1.11	0.79	+40.51%

Resistance (kw/m)			
Impact Resistance (Hv)	926.13	1198.45	-22.72%

Fig. 4.2 shows the comparisons between the UHTC at 1400℃ and 25℃ for chopped fibers. The overall change for the properties is represented by the percentage column.

We compared both the particulate and chopped fibers sections of the UHTC at 25℃ and 1400℃ to get a true understanding how well the material will function at operating temperatures.. Once again, however, the actual material is more likely to be a gradient, so this comparison will provide the extreme ends of the spectrum of properties for this material.

The green in the chart highlights where the material has improved properties, while red showcases where it is worse. The chart clearly shows that the theoretical UHTC loses Young's Modulus and Impact Resistance after heating; however, it has improved thermal shock resistance.

When comparing our UHTC to another UHTC, such as Silicon Carbide, it is very similar to SiC in some important areas that are necessary for its desired application. [16] The Young's Modulus for reaction sintered at 1400℃ SiC is 200 GPa and the impact resistance is 1000 Hv. While the theoretical UHTC has a lower young's modulus and impact resistance, it is still very close to Silicon Carbide. The comparable Young's modulus and impact resistance mean the material is similar in durability to changes in its structure and impacts from particles in the air flow to Silicon Carbide. Additionally, Silicon carbides thermal shock resistance is 0.297 kw/m, which means the theoretical UHTC has a higher thermal shock resistance. This indicates that our UHTC has a better ability to withstand sudden temperature changes, a useful trait for sharp leading edges. Overall the material shows similarities to Silicon Carbide, indicating that it can be used for similar applications as SiC. Considering that the UHTC is being calculated using lower end values, it may even be better than SiC in certain areas based on what its young's modulus actually is when created.

Properties	Theoretical UHTC (particulate) at 1400℃	Silicon Carbide at 1400℃	Percentage Difference
Young's Modulus (GPa)	186.03	200	-6.99%
Thermal Shock Resistance (kw/m)	1.08	0.297	+263.64%
Impact Resistance (Hv)	947.61	1000	-5.24%

Fig. 5.1 shows the comparisons between the UHTC at 1400℃ for particulate fibers and SiC at 1400℃. The overall change for the properties is represented by the percentage column.

Properties	Theoretical UHTC (chopped) at 1400℃	Silicon Carbide at 1400℃	Percentage Difference
Young's Modulus (GPa)	180.3	200	-9.85%
Thermal Shock Resistance (kw/m)	1.11	0.297	+273.74%
Impact Resistance (Hv)	926.13	1000	-7.39%

Fig. 5.2 shows the comparisons between the UHTC at 1400℃ for chopped fibers and SiC at 1400℃. The overall change for the properties is represented by the percentage column.

Considering that the ultimate goal of this research was to create a UHTC material that has improved strength, the fact the material does not sustain major losses in its properties is a good sign that it will have important uses at both room temperature and during flight at hypersonic speeds.

Conclusion

When we consider the potential usefulness of this theoretical UHTC, it seems that the best application is for sharp noses on the front and leading edges of the wings on hypersonic planes. These parts of the plane will receive the greatest impact from shockwaves. These spots are where the plane will experience the most damage from high temperatures and particle impacts from debris. The nose and leading edges would thus have to be strong to withstand the high temperature increases and maintain its structure. Additionally, the material will have to be highly resistant against constant bombardment from the hypersonic flow. Because the material is able to maintain a good portion of its properties at high temperatures, this is a good sign that it will be useful for hypersonic aircraft.

An important point of examination is what properties does the UHTC have that we can not see through only calculation. Throughout this paper, we have assumed that the material has distinctly separate regions for chopped fibers and particulate fibers. In reality, the material is more likely to be a gradient from chopped fibers to particulate fibers. Mathematically, it would currently be impossible to showcase this distinction. This would mean we would want to create the material and measure its properties.

We hope to take this research to a laboratory and create the material. Then, we could test the material in real hypersonic conditions to see how useful it will be in industrial applications.

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