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Composite materials used in Scramjet- A Review☆

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Abstract

A challenging thermo-fluids problem in scramjet engine is due to the use of hyper-velocity ducted flows along with no direct cooling path for the internal aerodynamics. The presences of composite materials potentially offer an efficient solution for these design related problems due to their high strength to weight characteristics and their high heat resistant properties. The application of composite Materials is extensive such as strength to weight ratio, low cost and ease of fabrication. Composites materials help in providing the combination of properties such as tensile modulus, compressive strength and impact strength and they have been established as highly efficient, high-performance structural materials and their use is increasing rapidly. The novel applications of composites in aircraft have been of main interest to the scientist as well as researchers for many years as found from reports. This paper mainly focuses on a brief review of the current status of composite materials such as Polymer matrix composites, Metal matrix composites and Ceramic Matrix Composites (CMCs), with their emphasis on various applications including Scramjet combustor.

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1. Introduction

The possibilities to fly at hypersonic speeds have been available in the aerospace industry since the development of

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multi-stage rockets. However, rocket propulsion only includes limited scope for extensive hypervelocity travel which led to research into various methods of propulsion at hypersonic speeds since the 50’s and more recently it has become obvious that Scramjet engines will most likely form the basis for the next generation of high speed propulsion[1, 2]. To date, there have only been short duration concept demonstrators flown to prove that Scramjet technology is feasible however the development of the technology is now reaching the stage where longer duration flights are required [3]. There are several experimental and computational works regarding scramjet combustor since 80’s and also different fuel injections techniques are also used such as single strut injection[33,37,38], two-strut injection[34], wall injection[35], cavity injection[36] etc. in order to enhance the performance of scramjet combustor.

Longer duration hypersonic flight brings with it unique structural challenges due to the extreme thermal loads experienced at speeds greater than Mach 5. In order to enable longer flight times at these speeds the thermal loads need to be managed so that the structure can survive. The thermal energy must be either distributed within the structure in a manner which keeps the temperatures to within the material limits or it must be removed from the vehicle [4]. This paper describes a brief review of the modern composite materials which can be used in scramjet combustor at hypersonic speeds such that structure can survive.

Nomenclature

PMC	Polymer matrix composites
MMC	Metallic matrix composites
CMC	Ceramic matrix composites

2. Materials for hypersonic aircraft (scramjet engine) composites (All temperature)

Composite materials offer great advantages over metals and ceramics. Not only are composite able to withstand very high temperature, they can also be lightweight. There are three main types of composites materials: polymer-matrix, metal-matrix, and ceramic-matrix

2.1 Polymer matrix composites (PMC)

Generally the degradation of polymer materials occurs when they are exposed to elevated temperatures. On a hypersonic vehicle the highest thermal loading, other than on the leading edges, will occur in the combustor where the pressure is at a maximum and the shock wave boundary layer interactions also cause localized hot spots. The ability to manage these thermal loads will require the use of high temperature materials in conjunction with the aforementioned thermal dissipation techniques. There are various high temperature materials, for example Nb-Cb752 (2300°C), C-SiC(1600°C) or Inconel(1400°C), that could potentially be used for the design of a Scramjet combustor [4,5]. There are however also other criteria which will affect the choices made in the design of a flight vehicle. Carbon Composite materials which are also known as Polymer Matrix Composites (PMC) potentially offer an efficient solution for these design related problems because the strength to weight characteristics and heat resistant properties are very much high in PMC. As the temperatures expected in the combustor are generally high enough, hence the most likely solution is also reinforced carbon-carbon (RCC). RCC is capable of withstanding extremely high temperatures whilst maintaining structural integrity. The methodology of getting into space requires an optimization of flight path and propulsion systems. The fundamental requirements are to accelerate to the required speed, and overcome the integrated effects of gravity and aerodynamic drag. Each of these processes is adversely affected by mass of the flight vehicle and low structural mass is a primary design objective. It is due to this low mass requirement that carbon composites become such an attractive option. The carbon composite structural mass can be as low as 25% of that of other materials. In addition to this however other extra structural mass must be considered, e.g. metal fuel manifold, which may result in an overall weight reduction of up to 50% [6].

2.2 Metallic matrix composites (MMC)

High temperature limits along with increased toughness and strength against ductility is the key features of MMC. These MMCs are frequently used on the outside skin of a hypersonic aircraft. Titanium-based materials normally are thought-about prime candidates for large-scale structural use within the framework and engines, as well as each the outer skin and also the internal structure. In sheet kind they might give the premise for economical, light-weight honeycomb or truss-core structural panels that might be unreal exploitation superplastic forming and diffusion bonding. As cast or extruded product, they might be appropriate for internal support structure and fittings. These materials mix lightweight weight with an incontestable capability of 1100°F in commercially accessible alloys Metal matrix composites that use atomic number 22 aluminides because the matrix will have vital stiffness and strength enhancements over their monolithic counterparts. [7]

Considering the general MMC field, the greater part of advancement has been engaged in the territory of light-metal frameworks, with a large portion of the accentuation being centered on aluminum matix composites [8]. Intermittent SiC particulates or stubbles are being utilized to strengthen A1 alloys for minimal effort, isotropically stacked structures. Consistent flexible monofilaments, for example, boron and SiC, and multifiber yarns, for example, graphite and aluminum oxide, are being utilized to strengthen anisotropic, elite aluminum matrix composites [9]. These composites join the light load and malleability of the aluminum framework with the light weight and high solidness and quality of the support. While most exertion has been centered on A1 matrix composites, magnesium and titanium matrices are additionally being created. Magnesium alloys are being fortified with graphite strands to create composites, essentially for space applications such as scramjet where light weight, high particular stiffness, and near zero coefficient of thermal expansion are needed. Titanium composites are being strengthened with SiC monofilaments to build solidness and temperature capacity [10].

The dominant part of exertion in the region of high-temperature MMCs has concentrated on the improvement of fiber strengthened super alloys. These composites utilize high-quality, high temperature strands to strengthen super alloy grids. Appropriate materials and creation process choice permits the strands to hold their high-temperature properties, while giving a malleable, oxidation-resistance network to supplement the properties of the filaments [11]. Fiber strengthened super combinations have exhibited a critical increment in admissible working temperature over aggressive super alloys and single crystals under engine conditions. The majority of this exertion has been with tungsten fiber fortified super alloy matrix composites, yet other high-temperature composites, for example, tungsten fiber strengthened niobium and SiC fortified super combinations, are additionally being considered[12-20].

Specialty-matrix composites are those which have a particular mix of fiber and matrix required to meet a given application [12]. Copper matrix composites, strengthened with tungsten strands or graphite yarns, are a sample of this kind of composite. The W/Cu composites exploit the high-temperature quality and rigidity of tungsten strands and the surpassing thermal and electrical conductivity of both W and Cu, to make a composite with a high-temperature quality better than any high-conductivity copper alloy. The Gr/Cu composites additionally have an extraordinary thermal conductivity, and moreover they give a lower thickness, higher modulus composite material with an extensive variety of accessible thermal expansion coefficients [12].

On the other hand copper itself features a smart thermal physical phenomenon however is significant and its higher use temperature is restricted by its low mechanical properties. Pitch-based high modulus atomic number 6 fibers have wonderful thermal conductivity--better than the copper itself within the direction of the fiber--and the incorporation of those fibers into a copper matrix will cause materials helpful for applications like heat exchangers [12]. The addition of the fibers reduces the density, will increase the stiffness, raises the temperature capability of the copper, and considerably improves the thermal physical phenomenon within the direction of the fibers.

2.3 Ceramic matrix composites (CMC)

It permits for higher temperature within the reaction-propulsion engine so making bigger burning efficiency (i.e. the upper the temperature, the move utterly the fuel bums that results in raised fuel efficiency and lower emissions) .The brittleness characteristic of CMCs is their major downfall. [21]

Ceramic Matrix Composites (CMCs) are projected to be used as light-weight hot structures in scramjet combustors. each a carbon/carbon (C/C) and carbon/carbon-silicon inorganic compound (C/C-SiC) material area unit being thought-about to be used in an exceedingly passively cooled combustor style for prime speed scramjet engine. The C/C-SiC survived the high-temperature scramjet combustor setting with little erosion. Fig. 2 represents the C/C-SiC panel mounted as the top wall of the 10-inch-long (25.4-cm-long), 6° diverging nozzle duct in Scramjet combustor. [21]

Ceramic matrix composites have been proposed for use as warm assurance materials and hot structures. At the Institute of Structures and Design of DLR in Stuttgart, a particular CMC variation, C/C-SiC has been created comprising primarily of carbon filaments implanted in a silicon carbide matrix. The manufacture of C/C-SiC CMC composites at DLR is separated into three stages. In the initial step, a carbon fiber strengthened plastic (CFRP) part is delivered, which can be performed in various ways. The favoured methodology is resin transfer molding (RTM) or utilizing autoclave innovation, yet warm squeezing or fiber winding are additionally adequate procedures. After the curing, the composites are tempered for 4 hours at 240°C (464°F) to finish the polymerization of the lattice. It is key to utilize a pitch (e.g., phenolic) with high carbon yield in this progression to make a lattice with adequate carbon content in the ensuing step [21]. In the second step, the CFRP composite is carbonized under dormant climate (nitrogen) at a temperature of 1650°C (3002°F) to change over the polymer lattice to undefined carbon. The outcome is a C/C part. The pyrolysis results in a plainly visible shrinkage of around 10% essentially in thickness and an infinitesimal system of breaks inside of the C/C composite is framed. The fiber groups remain for all intents and purposes in place. [21] In the third step, with the help of melt infiltration, the C/C component is siliconized. Then the component is put into a coated graphite crucible and solid silicon is added as granulated pure metal. After heating to over 1420°C (2588°F) (melting of silicon), the porous C/C component fills with liquid silicon owing to the presence of capillary effect of the micro-cracks and the low viscosity of the molten silicon [21-24]. In an exothermic reaction between the molten silicon and the carbon matrix, silicon carbide is formed along the micro cracks encapsulating the carbon fiber bundles. The siliconizing is implanted under vacuum at a temperature of 1650°C (3002°F). The resulting C/C-SiC composites contain three material phases [21-24].

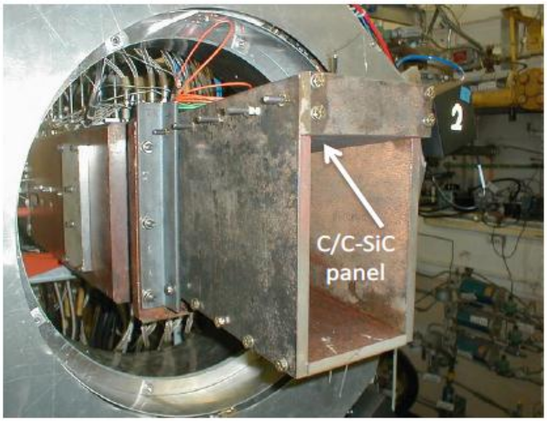

Fig. 1. C/C-SiC panel mounted as the top wall of the 10-inch-long (25.4-cm-long), 6° diverging nozzle duct in Scramjet combustor [21]

Ambreen Nisar et al [25] in their research work discussed about the importance of Ultra-high temperature ceramics, which are the most favorable materials for inherent application in thermal protection system under the extreme environment of hypersonic propulsion vehicle. They mainly worked on the recent advances and evaluation of high temperature properties of ZrB -based UHTC on propulsion system. In order to develop materials resisting the extreme environments for hypersonic vehicles, a hybrid carbon nanotube (CNT) reinforced UHTC-ZrB based composite is processed using spark plasma sintering (SPS). The ablation and oxidation of UHTC samples exposed to plasma arc jet proposes that CNT has a remarkable influence on the temperature of surface and oxidation resistance, which is confirmed via higher back face temperature in ZrB -CNT composite (of 1080°C 2 when compared to that of ZrB at 1030°C) indicating 2 dissipation of heat that will restrict hot-spot formation. Moreover, CNTs are observed to act as strenuous pathways and effectively "sealing" the grain boundaries, and making the composite survive in the harsh environment. Hence, effort should be made to balance the thermal response and oxidation resistance of the UHTCs against service temperature when choosing materials for extreme oxidizing and high temperature environment for hypersonic scramjet vehicles.

Richard Miles et al [26] worked on A Shape-Morphing Ceramic Composite for Variable Geometry Scramjet Inlets. In their research, they revealed that the growth of ceramic composites with three-dimensional fiber reinforcement architectures composed by textile methods has accelerated the prospective for active shape-morphing surfaces that can utilize in high temperature and variable pressure environments. This technology is of specific interest for hypersonic applications, where SCRAM jet engines need variable inlet geometry to achieve efficient flight over realistic flight profiles and flexible flight conditions. They additionally found in their examination that extensive temperature and pressure inclinations can be maintained without noteworthy contortion of the state of scramjet. These outcomes show that textile based CMCs are brilliant possibility for applications in hypersonic vehicles and hypersonic ground test facilities, where huge varieties fit as a fiddle and precise shape control are required in the vicinity of extreme temperature and pressure loads.

Due to the poor structural reliability of monolithic ceramics [27-30], they have yet to be registered to basic parts in scramjet engine. In light of their low crack durability, these materials show a high affectability to little cracks or defects inside of their microstructure. During the application of external loads, these materials become unsteadily in the ceramic, leading to brittle, catastrophic material failure Subsequent to the occurrence and size of these flaws are hard to control amid conventional ceramic processing furthermore amid operation in forceful situations, monolithic ceramics show a wide variety in quality properties. This absence of structural reliability is a noteworthy worry to designers and is at present constraining the utilization of ceramics for scramjet engine applications [27-30].

M. M. Opeka et al [31] work on Oxidation-based materials selection for 2000◦C + hypersonic aero surfaces revealed that hypersonic flight includes amazingly high speeds and gas temperatures with the orderly need for thermal protection systems (TPS). New high temperature materials are required for these TPS frameworks. A methodical examination of the thermodynamics of potential materials uncovered that low oxidation rate materials, which frame pure sizes of SiO2, Al2O3, Cr2O3, or BeO, can't be used at temperatures of 1800◦C (or more) because of problematically high vapour pressure which emerge at the interface of the base material and the scale. Vapor pressure contemplations give noteworthy knowledge into the generally great oxidation resistance of ZrB2-and HfB2-based materials at 2000◦C or more. These materials structure multi-oxide scales made out of an unmanageable crystalline oxide (skeleton) and a glass part, and this compositional methodology is suggested for further improvement. The oxidation resistance of ZrB2-SiC and other non-oxide materials is enhanced, to no less than 1600◦C, by compositional adjustments which advance immiscibility in the glass segment of the scale. Other applicant materials framing high temperature oxides, for example, uncommon earth mixes, are to a great extent unexplored for high temperature applications and might be alluring contender for hypersonic TPS materials.

David E. Glass [32] worked on Ceramic Matrix Composite (CMC) Thermal Protection Systems (TPS) and Hot Structures for Hypersonic Vehicles and found that hypersonic air-breathing vehicles deliver some unique thermal and thermal-structural challenges, such as sharp leading edges and structures with thin cross sections. These challenges can be overcome by using different type of CMC structures in Scramjet vehicle along with multiple TPS and hot structure approaches.

(1)

3. Conclusions

The review related to the composite material has shown that the scramjet combustor design is feasible with PMC, MMC as well as CMC materials. Composite materials offer great advantages over metals and ceramics. The following conclusions can be drawn on premises of the review which is discussed in the article.

- The composite materials having high stiffness/weight and strength/weight ratio provide noteworthy benefit in diminishing weight and increasing efficiency of scramjet engine

- Polymer Matrix Composites (PMC) potentially offer an efficient solution for design related problems in scramjet combustor because the strength to weight characteristics and heat resistant properties are very much high in PMC.

- Similarly high temperature limits along with increased toughness and strength against ductility is the key features of MMC.

- Ceramic matrix composites are another developing innovation to enhance the strength and unwavering quality of ceramic for high-temperature applications, for example, those found in scramjet engine hot section parts. Finally CMC permits for higher temperature within the reaction-propulsion engine so making bigger combustion efficiency.

This justifies the continuing analysis and any work regarding application of composite in scramjet, as this might represent an engineering style that would be flown within the close to future on long period scramjet flight tests. These works are going to be extended to incorporate totally different fuel varieties and combustor configurations sanctioning analysis of scramjets presently being thought-about for flight.

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