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PREVENTION OF EROSION BY INTRODUCTION OF CERAMIC MATRIX MATERIAL FOR RAMJET NOZZLE

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ABSTRACT

A ramjet engine is the simplest and the least complicated air – breathing engine that produces thrust by the principle of ram pressure without the use of compressors and turbines, unlike other air – breathing engines like turbojet and turbofan engines. A ramjet engine mainly consists of an inlet, a combustor and an exhaust nozzle. The solid propellant is burnt inside the combustor which generates large amount of gas having high pressure and temperature. The temperature ranges from 1700K – 2300K and the total pressure ranges from 0.2MPa to 0.7MPa respectively inside the combustor and nozzle. The gases produced leave the exhaust nozzle at very high velocity of about 300 m/s. Under these conditions of high pressure, temperature and velocity, the nozzle of the engine gets eroded and this might lead to structural failure. The combustion products are rich in oxygen which leads to erosion of surfaces that come in contact. Through this paper we aim to reduce the erosion by using composite materials along with a lining of ceramic material for the innermost layer of the ramjet nozzle. Although we could have restricted ourselves by only using composite materials, however an addition of ceramic layering will ensure minimum erosion as compared to composite materials as these materials are not appropriate for oxidizing environment.

General Terms

Conventionally ramjet nozzles are made up of steel, however the introduction of carbon composite material along with ceramic matrix material will enhance the properties of ramjet nozzle to withstand large temperatures and at the same time prevent oxidation.

Keywords

Ceramic material, Composite Material, Exhaust Nozzle, Ramjet Engine

1. INTRODUCTION

The Ramjet Engine is the simplest form of air – breathing engine that consists of:

a) Supersonic diffuser
b) Subsonic diffuser
c) Combustion chamber
d) Discharge nozzle section

A Ramjet Engine produces very high pressure ratios of 8 to 10 due to the fact that it does not have a mechanical compressor and turbine unlike other air – breathing engines.

Both the supersonic and subsonic diffusers convert the kinetic energy of the entering air to pressure rise, this is called as the ram effect and the pressure thus produced is called the ram pressure. From the atmosphere the air enters at a very high speed into the supersonic compressor where the velocity is reduced thereby the pressure increases, further the air is compressed into the subsonic diffuser. After the diffusion in the intake, fuel is injected into the combustion chamber where the fuel is mixed with the unburnt air due to which the temperature inside the combustion chamber increases to about 2000K which further leads to the buildup of pressure. The gases are allowed to expand in the combustion chamber towards the tail pipe and further allowed to expand in the nozzle section. The products leave the engine with a speed higher than the speed of incoming air through a convergent – divergent (C-D) nozzle. Due to this there is an increase in momentum of the working fluid which produces thrust. Generally the air enters the engine with supersonic speed, however is reduced to subsonic level to prevent blow out of the flame in the combustion chamber. The cycle pressure ratio of the ramjet engine depends upon the flight velocity, the greater the flight velocity the more is the pressure ratio and hence more the thrust produced. This is true until a condition is reached where the discharge nozzle gets chocked and thereafter the nozzle operates with a constant Mach number of 1 at its throat. Since the ramjet cannot operate under static conditions, due to this it is not self – propelling. To initiate the operation it must be given an initial velocity by some auxiliary means like launching rockets. The Ramjet Engine best operates under supersonic speed range having Mach number between 2 and 5.

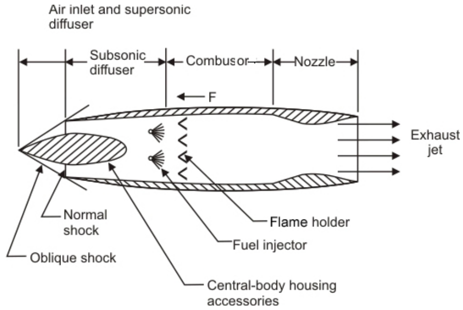

Figure 1: Schematic of a typical Ramjet Engine

Typically steel is used for the fabrication of ramjet nozzle. However the aim of this study carried out in the paper is to take into consideration the use of carbon – carbon composites along with ceramic matrix material for ramjet nozzle

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fabrication. The introduction of C-C composite material along with ceramic matrix material is important to prevent erosion of the ramjet nozzle particularly the throat section of the nozzle, which is more sensitive to heat and erosion. Erosion in the nozzle is caused due to high temperature exhaust gases coming out of the nozzle section. The use of carbon composites along with ceramic material will not entirely eliminate nozzle erosion but will prevent oxidation up to a certain extent and hence lead to increased lifetime of nozzle.

2. USE OF CARBON – CARBON (C – C) COMPOSITES

Carbon composites have high thermal conductivity, low thermal expansion, good frictional properties, high strength, high fracture toughness and it is thermally very stable. Due to its unique feature carbon – carbon composites are widely used in aerospace industry as a material for re – entry nose tips, in gas turbines and brake discs in aircraft. In a similar way C-C composites can also be used in the fabrication of the ramjet nozzle. However carbon is particularly susceptible to oxygen at elevated temperature and this leads to oxidation. The oxidation of C-C occurs in the presence of air (> 400°C) which is the main limitation of this composite material. Oxidation in carbon – carbon composites occur due to the high temperature of exhaust gases that are produced in the combustion chamber and nozzle section of the Ramjet engine. It is important to overcome the issue of oxidation in C-C composites to be able to continue their use as lightweight, high strength and high modulus structural material. Carbon reacts with oxygen in air to produce carbon dioxide (CO_2) and carbon monoxide (CO). It is this chemical property of carbon that restricts its ability to resist oxidation especially at very high temperatures. Such oxidation reactions occur on the external surface or internal pores of the composite material that is introduced during the fabrication process. The oxidation of C-C composite reduces the overall compressive strength of the material. It is also observed that during oxidation, oxygen attacks at the fiber/matrix interfaces which leads to decoupling of the fiber or matrix. Experiments have also shown that oxidation at high temperature may also lead to reduction in elastic modulus and flexural strength by 30 % and 50% respectively while at low temperature the strength is decreased by 60 % and Young's Modulus by 75 %.

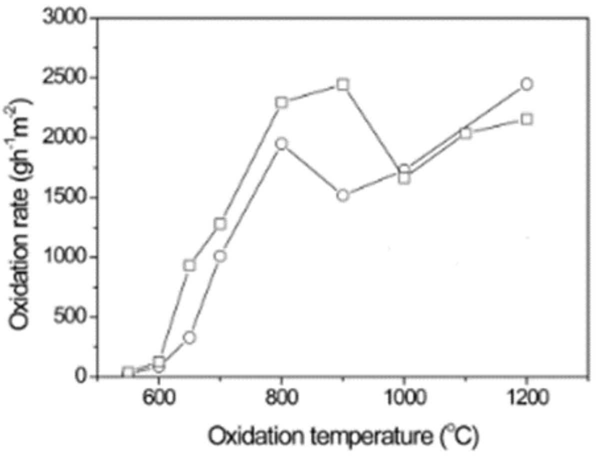

Figure 2: Variation of oxygen rate with oxidation temperature of C-C composite material

The graph above represents the variation of oxidation rate with increase in temperature. It can be clearly inferred that as the oxidation temperature increase the rate of oxidation also increase which leads to wearing awa of the carbon composite material.

Table 1: Comparision of the suitability of tungsten, pyrolytic graphite and C-C composite for ramjet nozzle

→ Increases pressure and temperature			
Requirement	**Tungsten**	**Pyrolytic Graphite**	**C-C composite**
Performance	Temperature limited	acceptable	Repeatable
Reliability	Acceptable	questionable	High
Cost	High	High	Moderate
Design	Complex	Complex	Simple
Weight	Heavy	Medium	Light
Growth potential	Very limited	Limited	High

3. USE OF CERAMIC MATRIX COMPOSITES (CMCs)

3.1 Ceramic Matrix Composites

In the above section of the paper we discussed about the utility of carbon – carbon composites for the fabrication of ramjet nozzle. However a major limitation posed by the carbon composite material is oxidation at very high temperature due to the exhaust gases produced at the nozzle section and burning of fuel in the combustion chamber. This section of the paper will focus on the use of ceramic matrix composite materials for ramjet nozzle fabrication. Although oxidation in the C-C composite materials can be prevented in a number of ways like by the addition of inhibitors, surface treatment, protective layer coating and micro – structural modification of carbon. Nonetheless the use of ceramic matrix composite (CMC) is a much more efficient way to prevent oxidation. Ceramic matrix like SiC (silicon carbide) can be used instead of carbon matrix which gives higher oxidation resistance than C-C composite. The composite is known as C/Si-C composite, which provides excellent oxidation resistance for long duration and is capable of withstanding very high temperature. This composite ceramic material is widely used in jet engines, gas turbine components and is the most preferred material for fabrication of ramjet nozzles. Hence carbon – fiber – reinforced Si-C is preferred over C-C composites for highly oxidizing and corrosive environment. C/Si-C composites can be used up to 1500°C for long duration and up to 3000°C for short durations.

3.2 Characteristics of CMCs

C/Si-C composites exhibit very high specific strength which can be operated at very high temperature range. The high thermal conductivity, low thermal expansion, excellent shock resistance property, high fracture toughness and good erosion characteristics makes it a favored material for the fabrication of ramjet nozzle. The outer casing of the ramjet nozzle is made up of steel. Inside the metal casing a C-C composite layer is deposited. The ceramic lining forms the innermost layer of the ramjet nozzle. It is the ceramic layer which

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encounters the high temperature, high speed combustion products of the ramjet combustion chamber.

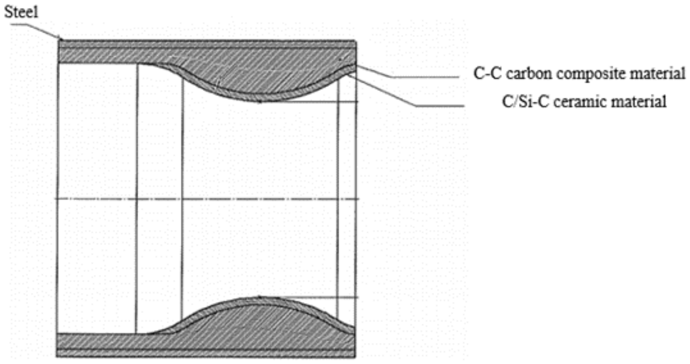

Figure 3: Configuration of ramjet nozzle

3.3 Mechanical Properties of CMCs

C/Si-C composites are developed to protect the C-C composites from oxidation. From Figure 4. , it can be seen that the mechanical properties of C/Si-C composites are better at higher temperature than at the room temperature. The maximum temperature range of C/Si-C is 1500-1700°C under stationary conditions, however these composites can be used up to 3000°C when the lifetime amounts to only a few minutes. The interfacial layer of carbon in the C/Si-C composite helps in diverting the cracks that are formed on the material surface which reduces the matrix – fiber bonding which further helps in the reduction of oxidation of the composite material.

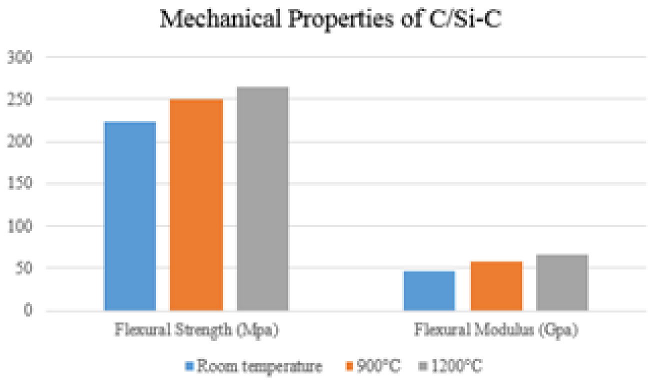

Figure 4: Mechanical properties of C/Si-C at high temperature

4. FABRICATION PROCESS OF C/Si-C CERAMIC MATERIAL

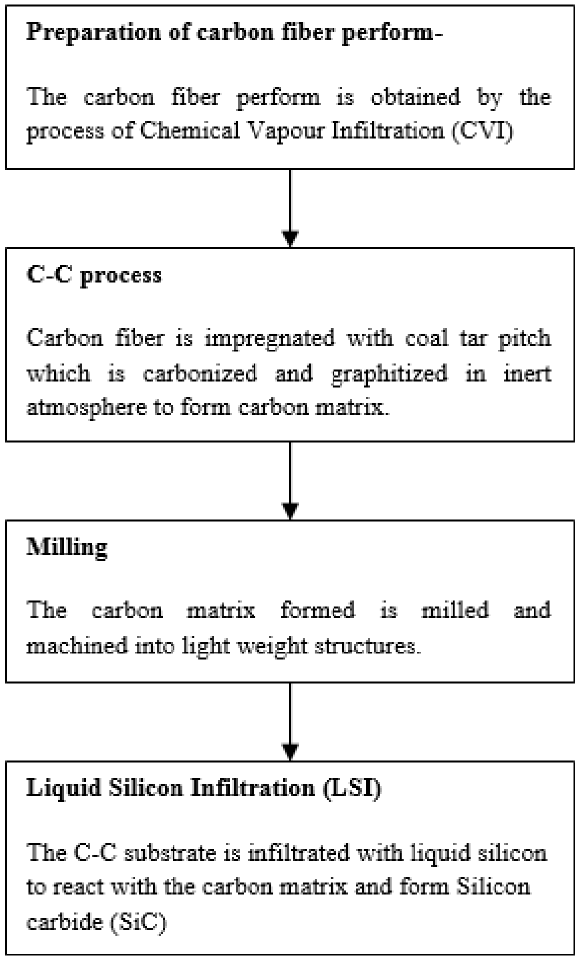

Figure 5: Fabrication process of C/Si-C ceramic composite

5. OXIDATION RESISTANCE OF C/Si-C COMPOSITE

As C-C composites are subjected to an oxidizing environment at temperature > 400°C, the carbon fiber reacts with oxygen and this leads to oxidation of the carbon composite and results in loss of strength of the composite material. However the application of SiC in C-C composite acts as good oxygen barriers as it has excellent refractory properties. As highlighted in the fabrication process that SiC is formed by liquid silicon infiltration in C-C composite. From figure 6. It can be inferred that mass loss is very low for silicon infiltration with increasing time as compared to without silicon infiltration which increases with time. An interfacial zone is formed between the C-C composite and SiC which prevents the formation of cracks and therefore increases the oxidation resistance while transverse cracks are formed and diffusion of oxygen takes place through these cracks which are formed when there is no silicon infiltration, this leads to oxidation of the composite material.

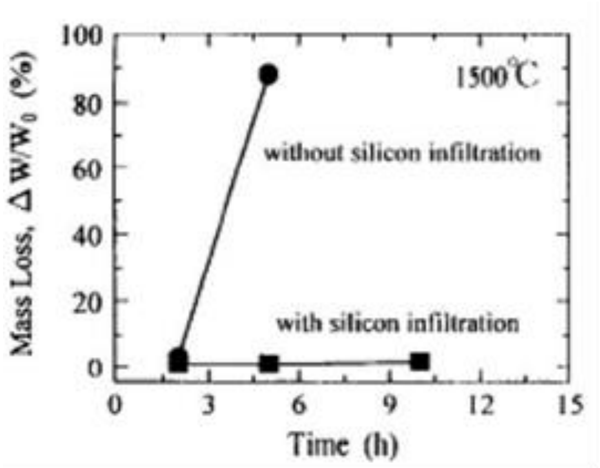

Figure 6: Effect of silicon infiltration on mass loss with time

However oxidation may limit long term application of the composite ceramic material in high temperatures. The oxidation of composite ceramic material may arise due to matrix micro – cracks that form on the surface or due to volatization of protective oxide (silica) layer. This can be overcome by developing oxidation – resistant interface by matric – oxidation inhibitors or surface coating the composite matrix. Ceramic material surface coating includes glass coating the surface of C/Si-C composite material with borate, phosphate or silicate. Glass coating reduces oxidation to great extent. Apart from glass coating, metal coating can also be done with alloying metals like Cr which on oxidation form Cr_2O_3 and when this reacts with SiO_2 it forms a glassy material that acts like an anti – oxidant layer. Further ceramic material coating of Si_3N_4, $MoSi_2$ can also be applied on the surface which also has outstanding anti – oxidant properties.

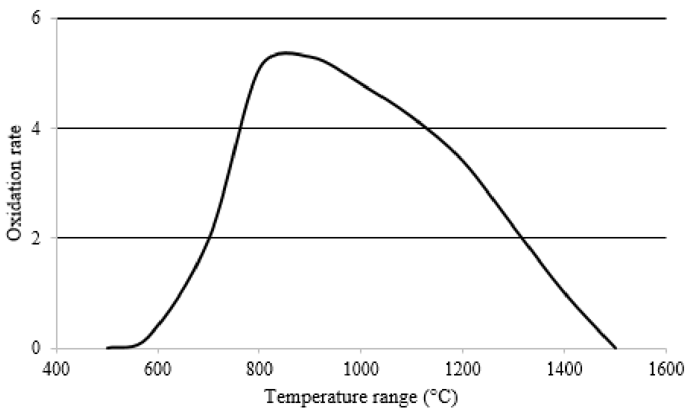

Figure 7: Dependence of C/Si-C oxidation rate with temperature

The graphical representation above shows the dependence of initial oxidation rate with temperature for C/Si-C composite. It can be interpreted that as the temperature increases the rate of oxidation decreases. Hence this dependence makes C/Si-C ceramic composite a desirable material for ramjet nozzle fabrication as it can withstand large temperatures and yield low oxidation rate and prevent nozzle erosion, hence increasing the lifetime of nozzle. The existence of SiC particles not only decreases the oxidation rate but also maintains the integral shape of C-C composite material.

6. CONCLUSION

The application of C-C composite material in ramjet nozzle offers a great potential due to its high strength, high thermal conductivity, low thermal expansion and thermal stability. However at temperatures greater than 400°C in the nozzle section it leads to oxidation which is a drawback of C-C composite. To improve the oxidation resistance and prevent erosion the addition of SiC in carbon composite formed by liquid silicon infiltration provides stability to the carbon composite material. The C/Si-C formed is a ceramic matrix material that is used as the inner lining for the ramjet nozzle fabrication along with C-C composite layer. The mechanical properties like flexural strength, flexural rigidity is very high. The C/Si-C ceramic composite can be can be suitably operated at high temperature without oxidizing the composite material. Silicon infiltration process creates zone between C-C composite and SiC which prevents formation of cracks, thereby increasing the oxidation resistance. It can be safely operated under high temperature up to 1500°C for long duration and up to 3000°C for short durations. Hence this makes C/Si-C ceramic composites as the best suited material for ramjet nozzle. It does not entirely eliminate erosion but can reduce the extent by improving the nozzle material properties. Although C/Si-C ceramic composites do not undergo vigorous oxidation, however oxidation my occur due to matrix micro – cracks that form on the material surface. Oxidation can be prevented by developing oxidation resistant interfaces, by developing matrix oxidation inhibitors and by surface coating. Surface coating includes glass coating with materials like phosphate and silicate or coating with metal alloys like chromium and ceramic coating on the surface can provide excellent oxidation resistance. Hence, the ability of C/Si-C ceramic composite materials to withstand very high temperatures without getting oxidized makes it the best material to be used for the fabrication of ramjet nozzle which would help prevent erosion of the nozzle to large extent and hence increase the lifetime of ramjet nozzle.

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