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Parametric study of Composite Cryogenic Materials used for Propellant Tanks

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ABSTRACT: In this study, the types and characteristics of composite cryogenic materials used in propellant tanks; storage containers are discussed. The impact of low temperatures on various materials and mechanical properties are discussed. The scientific advancement of cryogenic materials is studied. The limitations of cryogenic materials research and application for propellant tank, storage are outlined in order to provide recommendations for future container material development. Carbon fibre composites, ceramic matrix composites, and ultra-high temperature ceramics are among the most commonly used cryogenic materials for propellant tanks, storage vessels. However, different grades of these materials have different applications, which must be considered in conjunction with their high temperature tolerance, corrosion resistance, low density in combination with sufficient mechanical properties, and other factors. However, as the demand for space propellant tanks, storage vessels grow, so does research into high-specific-strength cryogenic materials such carbon fibre composites, ceramic matrix composites, and ultra-high temperature ceramics.

KEYWORDS: Carbon fibre composites, Ceramic matrix composites, Ultra-high temperature ceramics, Propellants, Parametric

I. INTRODUCTION

The construction of advanced space vehicle with futuristic capabilities such as low cost launch vehicle, single stage to orbit (SSTO) and reusable launch vehicle, goal is to drastically reduce launch costs while also strengthening payload capability. Cryogenic propellant tanks are one of the most important parts of any spacecraft. The tanks take up a lot of space and add a lot of weight to the spacecraft, thus they're the most important weight-saving components. The entire service performance of the spacecraft is determined by a lightweight cryogenic propellant tank [1].Composite materials have higher strength and lower density and have the potential to reduce weight by 25% compared with aluminium alloy tanks [2]. Liquid hydrogen and liquid oxygen fuel tanks operate at temperatures of 253 ° C. and 183 ° C, respectively. Furthermore, the working pressure of cryogenic propellant tanks is typically kept between 0.2 and 0.3 MPa in order to keep the fuel in a liquid state at low temperatures and preserve the vehicle's overall stability [3].With the advancement of composite technologies, particularly carbon fiber, ceramic matrix composites, ultra-high temperature ceramic matrix and their progressive use in aerospace, composite cryogenic tanks have become the principal development direction of lightweight spacecraft. As compared to traditional materials, composites have high specific strength and modulus, low density and excellent fatigue resistance. This review discusses the materials used in composite and ultra-high temperature ceramic matrix composite, ceramic matrix composite and ultra-high temperature ceramic matrix composite, specific strength and modulus, low density and excellent fatigue resistance. This review discusses the materials used in composite and ultra-high temperature ceramic matrix composite an

Carbon fiber

Carbon fiber is a polymer and is once in a while known as graphite fiber. It is very hard material and lightweight at the same time. As compare to steel carbon fiber has double stiffness and five times stronger and lighter as well. That's the reason it is called as ideal manufacturing material and many engineers and designers prefers carbon fiber for manufacturing.Carbon fiber is reinforced material because it is made up of thin, strong crystalline filaments of carbon. It can be fine than standard human hair and it can gain strength by twisting it like thread.

Characteristics of Carbon fiber:

- High stiffness
- High tensile strength
- High chemical ratio
- Low weight to strength ratio



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• Low thermal expansion

Due to these characteristics carbon fiber is widely used in industries such as aerospace, military, automotive and recreational applications [5-6].

Ceramic matrix composite

Ceramic matrix composites are the combination of ceramic material and reinforcing ceramics which is also known as metal phase. CMC is recognised by its uniqueness that is the reinforcement and the matrixes are ceramic. CMC is consisting of ceramic fibers inserted in ceramic matrix, which forms ceramic matrix strengthens material. CMC is also known as subgroup of both components ceramics and matrix.

Characteristics of Ceramic matrix composite:

- High thermal shock
- High temperature resistance
- High tensile and compressive strength
- Low resistance
- Lightweight due to low density

Ceramic matrix composites are very popular in many industries like aerospace sector (gas turbines, structural re-entry thermal protection) and energy sector (heat exchangers, fusion reactor walls) [7].

Ultra-high temperature ceramic matrix

Ultra- high Temperature Ceramic Composites (UHTCC) is made up of 2.5D woven carbon fibre soaked with Hafnium DiBoride (HfB₂) Powder and pyrolytic carbon (PyC). This matrix is created by using chemical vapour infiltration (CVI) [8].

Characteristics of Ultra high temperature ceramic matrix:

- High strength to weight ratio at high temperature.
- High thermal shock resistance.
- Highest melting point.

UHTCC are a class of recalcitrant ceramic matrix composites, which tries to beat the cut-off points related with at present utilized CMCs (C/C and C/SiC) in aerospace field as thermal protection systems (TPS) and rocket nozzles.

II. LITERATURE REVIEW

Wenxun Huang et.al (2021) Progress in research on composite cryogenic propellant tank for large aerospace vehicles, the development of composite cryogenic tanks in the near future will move towards lightweight, large scale and diversified composites as a result, the manufacturing costs of aerospace vehicles can be substantially reduced while considerably increasing their carrying capacity [9] Jorg Hohe et al. (2021) observation was made on a specimen made of M46J/ER451 material (material A) with a significant potential for thermally induced micro cracking because to a large fiber-matrix stiffness mismatch. The interior surface of the pores reveals an initially brittle failure, followed by plastic deformation, converting the original crack-like defects into three-dimensional pores. Rather than being a general feature of the failure of the M46J/ER450 material, the observation is limited to a single position of this specific fracture surface. Nonetheless, when the test temperature is reduced to the cryogenic region, the brittle M46J/ER450 is the only one of the three reference materials to show a decrease in the primarily matrix controlled failure load values under tension perpendicular to the fibre direction. This discovery suggests the development of thermally induced micro cracks, given the typical increase in the strength of polymeric materials in the cryogenic zone. There were no signs of heat micro cracking in the other two reference materials. [10] Daining Fang (2020) studied the tension and bending properties of unidirectional and quasi isotropy CFRP laminates at different temperatures and thermal cycles. X-ray microscopy and other methods were used to characterize the morphologies of laminates and figure out the evolution of the mechanical properties [11]. S.K. Pradhan et al. (2020) among the other propellants, liquid propellant has been shown to be the most reliable. However, hybrid propellant can be considered a future reference as a propellant source.



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Reduce the consumption of hydrazine and hazardous propellants while obtaining the needed amount of specific impulse from a green propellant. One of the most pressing challenges in terms of pollution and human health is the environment. Alternative green propellants include ethanol, hydrogen, oxygen, kerosene, paraffin wax, and HTPB. Salts such as hydroxyl ammonium nitrate and emim ethylsulfate can be utilised as a propellant for two separate purposes: higher thrust for a shorter period and less thrust for a longer period as needed to save money on two different types of propellant and stages [12] Paula Cristina Gomes Fernandes et.al (2019) study on the mechanical properties of solid composite propellant used as a Gas Generator studied d formulations of solid composite propellant of gas generator type, evaluating the influence of additives on the material mechanical properties and Changes in the concentration of other additives (burning catalyst, plasticizer) [13]. Shanyi Du et.al (2017) studied the effect of surface treatment on the interfacial adhesion performance of aluminum foil/CFRP laminates for cryogenic propellant tanks, due to the surface treatments like corrosion method and addition of flexible layer applied, the interfacial adhesion performance of Al foil/CFRP laminates after cryogenic cycles improved significantly, which indicated that the T5000 layer did play the role of flexible connection on the interface as anticipated [14] Sufang Tang et.al (2017) designed, preparation and properties of carbon fibres reinforced ultra-high temperature ceramic composites for aerospace applications reviewed the C/C-SiC-UHTC and C/UHTC composites are promising materials for engine propulsions and hypersonic vehicles due to their excellent ultra-high-temperature performance, such as good oxidation and ablation resistance, high strength and fracture toughness, good defect tolerance, and good thermal shock resistance. The composites can be fabricated according to the different processing routes from gaseous or liquid precursors, slurries as well as solid addition [15]. Zhixiong Wu et al. (2015) cured diglycidyl ether of bisphenol F (DGEBF) epoxy resin system was changed in this investigation by the addition of E102, ETBN, and IPBE. At 77 K, the effect of matrix change on the ILSS was studied. Among all the tested situations, IPBE was the most successful for enhancing the ILSS of the composite at 77 K, resulting in a maximum of 14.87 percent improvement in shear strength over the unmodified sample. IPBE enhanced the hardness of the epoxy matrix and the interfacial adhesion strength between glass fibres and the epoxy matrix, according to micrographic analyses [16]. Md S. Islam, et.al (2015) woven fiber reinforced composite materials exposed to cryogenic environment were investigated in this paper with the objective of using them in cryogenic propellant tanks [17]. J.E. Fesmire et.al (2015) layered composite thermal insulation system for nonvacuum cryogenic applications. Overcoming vapor drive toward the cold side and preventing moisture accumulation inside are the major challenges of insulating complex cryogenic equipment in the ambient environment [18]. M.J. Robinson, et.al (2015) composite cryogenic propellant tank development the need for superior fatigue resistance, corrosion resistance and minimum thermal strain in reusable cryogenic tanks may make composite designs more viable than lightweight, thin gauge metal ones[19]. D.M. Grogan (2015) studied combined experimental and numerical approach to the design and analysis of tape-laid thermoplastic composite cryogenic tanks. A detailed material and defect characterisation of automated tape-laid CF/PEEK is undertaken using optical micrography and 3D X-ray CT (computed tomography) as well as cryogenic testing to investigate damage formation [20].

III.PROPERTIES

Tensile Strength:

Tensile strength is the capacity of a material to endure a pulling power and alludes to the breaking strength of a material while applying a power equipped for breaking many strands of a material at the same time, at a steady pace of expansion. It is generally estimated in units of power per cross-sectional area. The tensile strength of Carbon fiber composite is 3530MPa. Ultra-high temperature has tensile strength of 330 MPa & Ceramic matrix has 130MPa. By comparing the value of 3 composite materials Carbon fiber composite has great tensile strength than Ultra high temperature and Ceramic matrix [21].

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Fig 1. Materials variation along with the tensile strength

Hardness:

Because a large number of CMCs and UHTCs are currently being developed, it is critical to characterize their mechanical properties. Because hardness is a material feature that can be evaluated with modest effort on the surface of tiny specimens, it is appealing for a quick qualitative assessment of material properties and can also be used for quality control. Tabor's rule states that in many metals, hardness is proportional to yield strength. [22]. Phase composition, wear, and machinability are some of the other material attributes that might be linked to hardness. Hardness is assessed by indenting the studied materials with indenters of various shapes and measuring the size of the resultant indent for homogeneous materials. Hardness of some Carbon Fiber Composites, Ceramic Matric Composites, Ultra high Temperature ceramics are shown in the graph-



Fig 2. Materials variation along with the hardness

Poisson's Ratio:

In engineering analysis, poisson's ratio is a needed constant for estimating the stress and deflection properties of materials (plastics, metals, etc.). It is a constant used to calculate the stress and deflection parameters of beams, plates,



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shells, and rotating discs. When it comes to plastics, temperature variations, the severity of stresses and strains, and the loading direction all have an impact on Poisson's ratio. These factors, on the other hand, rarely modify the average range of values enough to affect most practical computations, in which this constant is often of secondary relevance. The Poisson's ratio v is commonly used to describe a material's elastic properties[23]. When a longitudinal stretching force is given to a solid, it begins to stretch. The cross-section of the material shrinks in the great majority of situations during this stretching. The Poisson's ratio depicts how a deformable body's cross-section varies when stretched longitudinally (or compression). Poisson's Ratio of some Carbon Fiber Composites, Ceramic Matric Composites, Ultra high Temperature ceramics are shown below-



Fig 3. Materials variation along with the poisson's ratio

Young's Modulus:

A material's Young's Modulus is an unchangeable attribute. Temperature and pressure, on the other hand, play a part. The stiffness of a material is defined by the Young's Modulus (or Elastic Modulus). To put it another way, it refers to how easy it bends or stretches. Young's modulus varies with temperature and can be realised by changes in interatomic bonding between atoms, hence its alteration is discovered to be dependent on changes in the work function of the metal. In all orientations of a material, Young's modulus is not necessarily the same. Most metals and ceramics, as well as many other materials, are isotropic, meaning that their mechanical properties are the same regardless of their orientation. Metals and ceramics, on the other hand, can be treated with impurities, and metals can be mechanically manipulated to create directed grain structures[24]. The Young's modulus of these materials will change depending on the direction of the force vectors. Young's Modulus of some Carbon Fibre Composites, Ceramic Matric Composites, Ultra high Temperature ceramics are Shown below

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Fig 4. Materials variation along with the young's modulus

Material	Hardness (kg/mm ²)	Young's Modulus (GPa)	Poisson's Ratio	Tensile Strength(GPa)
SiC	2500	448	0.168	8.40
HfC	2300	350-510	0.18	0.5-1.25
ZrC	2700	350-440	0.191	0.79-0.874
TaC	2500	285-560	0.24	42.3
HfB ₂	2800	480	0.21	37.3-58.6
ZrB ₂	2300	489	0.16	42.6-56.9

TABLE I. Properties of Materials

IV. CONCLUSION AND FUTURE SCOPE

The necessity for cryogenic propellant tanks and storage vessels is expanding in order to accommodate the future growth of the cryogenic propellant sector. As a result, comprehensive study on cryogenic materials and their cryogenic properties is critical in order to build a cryogenic database of important materials. When compared to aluminium alloy tanks, composite materials have stronger strength and lower density, and they have the capability to reduce weight by 25%. The cryogenic capabilities of composites have gained a lot of attention as a cryogenic liquid storage and transit container, and a lot of literature has been evaluated in depth in recent years. Composites' low-temperature mechanical properties are influenced by matrix, fibre, and interface.

The properties considered for the study are boiling point, hardness, poisson's ratio, Young's modulus and tensile strength. Each of the composites have their pros and cons but when looking for composite cryogenic material for



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propellant tank, ceramic matrix composites can be considered with a fairly high Young's modulus and its tensile strength is desirable which shows good mechanical performance, compared to other selected materials. In general, the bonding strength of the polymer molecular chain increases as the temperature drops. The Young's modulus and tensile strength of the ceramic matrix rise as a result. Carbon fibre, unlike polymers, has a lower temperature effect on its strength. When compared to the ceramic matrix or the fiber-resin interface, the impact of this drop on the entire composite can be overlooked. In case of passion's ratio when a longitudinal stretching force is given to a solid, it begins to stretch. The cross-section of the material shrinks in the great majority of situations during this stretching. The Poisson's ratio depicts how a deformable body's cross-section varies when stretched longitudinally Tabor's rule states that in many metals, hardness is proportional to yield strength.Future research will focus on developing new lowtemperature materials with high performance and low cost. The institution intends to create a database of mechanical properties of low temperature materials such as carbon fibre composites, ceramic matrix composites and ultra-high temperature ceramics.

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