Abstract

In the space sector, there is an increasing need to reduce the costs associated with launching payloads into orbit, as current expendable launch vehicles entail significant expenses. Therefore, considerable engineering efforts are focused on the development of Reusable Launch Vehicles (RLVs) to reduce launch costs and establish a more cost-effective method for accessing space. RLV functioning necessitates exposure to the atmosphere at high Mach numbers, resulting in temperatures reaching 2000ºC during re-entry. As a result, proper heat load management is critical to avoiding damage.

The Thermal Protection System (TPS) is a crucial element of space vehicles designed to shield them from the aerothermal heating experienced during atmospheric entry. The objective of TPS is to retain the high specific strength at elevated temperatures. Among metallic options are metallic matrix composites (MMC), Ni-based superalloys, and titanium, all exhibiting commendable specific strength, albeit experiencing a drastic decline around the 1000ºC range. When considered collectively as ceramic matrix composites (CMCs), materials such as C/SiC, advanced carbon/carbon (ACC), and SiC/SiC emerge as noteworthy options providing high strength at elevated temperatures (>1000ºC), a critical requirement for RLVs. CMCs can be made either by conventional fabrication techniques (e.g. hot pressing, cold pressing and sintering, reaction sintering, powder sintering, etc.) or by new unconventional methods such as polymer infiltration pyrolysis (PIP), reactive melt infiltration (RMI), and Chemical vapour infiltration (CVI). CMCs with their best achievable properties are manufactured worldwide by a gaseous route known as (CVI) which works on the basic principle of thermal decomposition of a reactive gaseous mixture to form a solid product.

Traditional fabrication methods like welding, extrusion moulding, and forging are generally inadequate for realizing the potential of CMC components due to their size or complexity. Additionally, repairing damaged parts and detecting flaws in larger components pose significant challenges due to their intricate shapes. To facilitate processing, sizable components are often divided into multiple segments. This approach allows for the simpler fabrication and thorough inspection of smaller components, ensuring high quality and improved safety. If any defects are detected, the affected segments can be replaced with new ones, contributing to efficient maintenance. Consequently, the utilization of suitable joining technologies is essential, for bonding ceramic-to-ceramic and ceramic-to-metal, to constructing specific engineering components and fulfilling the necessary criteria. Therefore, the present study focuses on the joining of C/SiC-to-C103 alloy, C/SiC-to-C/SiC, and SiC-to-SiC ceramics. A brief description of each type of joining is given below:

(1) Joining of C/SiC to C103 alloy

Carbon fibre-reinforced SiC (C/SiC) composite is joined with niobium-based alloy utilising commercially available Ticusil® and Cusil® alloy braze filler materials. No cracks or voids were found

at the C/SiC-C103 interface and the joints were microstructurally sound and fault-free. XRD and EDS suggested the formation of various thermodynamically stable intermediate brittle phases (e.g., TiC, Nb_2C, and Ti_5Si_3) whose concentration is governed by the Ti content of the alloy. The results show that adding Ti promotes the growth of “nails”, a phenomenon favourable for robust joint quality. However, high Ti content deteriorates the bond strength due to the formation of significant brittle intermetallic phases, causing premature delamination of the joints. The response surface methodology (RSM) is employed to examine the interactions among various operating parameters. a maximum average LSS value of 16 MPa was reached for the Cusil-based joint when the brazing temperature of 840ºC, a reaction time of 10 min, and a cooling rate of 5◦C/min were maintained.

(2) Joining of C/SiC composites

A novel brazing filler formulation with carbon nanotubes (CNTs) incorporated in the Ni-30Si alloy is designed to enhance the bonding of C/SiC composites. The CNT content is varied from 0 to 15 vol.% in the filler alloy. Ni-Si-CNTs alloy containing 10% CNTs exhibited good bonding for C/SiC composites and rendered the highest LSS (21 MPa) and Rockwell hardness (84.6) values, which is ~147% higher than the joint without CNTs addition. The microstructure analysis revealed that incorporating CNTs promotes the formation of new phases such as Ni_2Si, Ni_3Si_2, and β-SiC reduces the overall CTE mismatch and provides additional reinforcement to the interlayer. Significant reduction in the CTE values caused lower thermal residual stresses while cooling, leading to better bond quality. The fracture surface analysis exhibited substantial CNTs rod pull-out, a phenomenon highly desirable for enhanced bond strength and non-catastrophic failure of the joint. CNTs loading >10 vol.% significantly reduced the joint strength as a result of agglomeration, void formation, and poor wettability.

(3) Joining of monolith SiC ceramics

SiC ceramic was joined using Ni-30Si filler, incorporating varying concentrations of Mo (up to 12 at%) at 1300 °C. This approach is adopted as the presence of graphite at the interface of the joint degrades the mechanical properties of the bond. This study investigates the effect of Mo in Ni-30Si alloy on the brazing of SiC at 1300°C, to regulate interfacial reactions and reduce residual stresses by decreasing overall CTE values throughout the brazing process. The addition of Mo up to 8% efficiently suppresses graphite accumulation by converting it into Mo_2C+Ni_3Mo_3C phases, lowering the CTE to 5.4×10^{-6} /°C. The graphite-free joint exhibits an LSS of 107 MPa, which is nearly three times greater than the joint with graphite. On further increasing the Mo-content beyond 12%, the interactions between the filler and SiC are reduced as a result of the non-homogeneous dispersion of Mo. Thermodynamic analyses are performed to provide a comprehensive understanding of the underlying mechanisms responsible for the formation of distinct phases in brazed joints. Thus, the present study strongly suggests that vacuum brazing can be successfully used for joining C/SiC-to-C103, C/SiC-to-C/SiC, and SiC-to-SiC for various aerospace applications.