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Experimental evaluation of static and fracture behaviour across manufacturing stages of CMC material

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Objective

Mechanical characterization of Ceramic Matrix Composite (CMC) was performed using a comprehensive experimental tests composed of static tests (tensile, compression and three point-bending) on all manufacturing stages (CFRP, C/C, uncoated and coated CMC) and fracture tests (DCB, ENF and SENB) on final coated CMC. As the final mechanical behaviour of the CMC material is the result of all the changes induced by manufacturing stages, it is important from a scientific and technical point of view to understand not only the change of the main mechanical and constitutive properties, but also the failure modes that characterize each stage. Therefore, the main objective of the research activity is to analyze the manufacturing-induced changes in mechanical properties before and after pyrolysis and silicon infiltration. Further, SiC surface coating effects were also evaluated comparing the mechanical properties with uncoated CMC. Finally, fracture tests have been carried out on the final CMC coated material to provide not only the fracture toughness values both in mode I and II, but also an understanding about fracture mechanism. The overall activity will help to analyze the underlaying failure mechanism in case of static and fracture failure using mechanical properties to refine manufacturing process and damage tolerance parameters to define the design criteria of the components in aerospace industry.

Materials and Methodology

CMC composite material is manufactured using Liquid Silicon Infiltration (LSI). The manufacturing process starts with a 2x2 impregnated fabric with phenolic resin used to form CFRP. This laminate then undergoes a pyrolysis process at high temperature evaporating resin, and an amorphous porous C/C composite is formed. Then, liquid silicon is infiltrated in that C/C composite to finally develop C/SiC CMC. Finally, SiC surface coating is applied to improve mechanical properties. Static tests have been performed using two layup with orientation 0°/90° and ±45° according to ASTM standards and six samples for each type of test were considered. All tests were carried out on universal servo hydraulic material testing system MTS810 with a maximum load capacity of 100 kN. During tensile tests two extensometers were attached to the gauge area of the sample to measure the axial and transversal strain, which allows evaluating stress-strain behavior and Poisson ratio. For the fracture tests, mode I interlaminar fracture energy was evaluated by a Double Cantilever Beam (DCB) test according to ASTM D5528 standards. Specifically, piano hinges were glued to the outer surfaces of the sample having an initial pre-crack length of 53 mm in the half thickness of the sample. DCB test is performed in several steps of loading and unloading cycles and the crack propagation during each cycle is measured using a DRS system capturing 25 images/second. To evaluate mode II fracture energy, End Notch Flexural (ENF) test was carried out on the sample having similar geometry as in DCB test and 3-point bending load is applied to generate mode II sliding crack using AITM standards. Finally, to measure fracture toughness value, Single Edge Notch Bending (SENB) test is performed on sample having notch with pre crack of 0.6 mm in the lower surface of in the thickness direction of the sample. 3-point bending load is applied according to ASTM C1421 standards and load deflection curve is developed.

Results and Discussion

Static tests on all four stages namely (CFRP and pyrolysed C/C, uncoated CMC and coated CMC) showed a consistent stress-strain behavior confirming the reproducibility of the tests. During initial two stages, CFRP and pyrolysed C/C, the mechanical strength and failure strain is leading in CFRP stage because of minimal porosity and stronger fiber-matrix interphase, while after pyrolysis, strength reduce enormously due to degradation of fibers at high temperature and removing of matrix (phenolic resin),. After silicon infiltration, carbon fibers react with silicon to form a SiC matrix and mechanical strength and strain significantly increase. Compressive strength of coated CMC in 0°/90° is found to be 42% higher than uncoated CMC while 8% higher in ±45° layup than uncoated CMC. This increase is associated with the failure mechanism during test, as micro-

buckling and kink bad initiation and coating surface might suppresses the crack on surface. During tensile and 3 point-bending tests, failure is mainly influenced due to tensile loading resulting fiber failure in 0°/90° layup and matrix cracking and fiber rotation in ±45°, hence coating effects remain negligible. Regarding fracture tests results, which has been carried out only on final coated CMC as coating changes mainly the mechanical behaviour of the specimen surface, mode I and mode II fracture energies and fracture toughness values were respectively 410 J/m², 631 J/m² and 7.61 MPa m½. **Conclusion**
Results of static tests showed that failure mechanism during tests in 0°/90° layup is mainly influenced by fiber failure, while in ±45° composite it is mainly governed by matrix cracking and fiber rotation. After each stage of manufacturing, significant changes in mechanical properties are observed due to manufacturing process at each stage. Results of fracture tests revealed that coated CMC has strong resistance to crack growth in both mode I and mode II crack opening. Finally higher fracture toughness and work of fracture (WOF) values under bending loads indicate enough toughness to arrest the small cracks before reaching the failure.

Primary author: ULLAH, Sana (University of Salento)

Co-authors: Dr DE FENZA, Angelo (Italian Aerospace Research Centre (CIRA)); Dr SCARSELLI, Gennaro (University of Southampton); Dr DE STEFANO FUMO, Mario (Italian Aerospace Research Centre (CIRA)); Dr NOBILE, Riccardo (University of Salento)

Presenter: ULLAH, Sana (University of Salento)

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