POLITECNICO DI MILANO

PhD in INGEGNERIA AEROSPAZIALE / AEROSPACE ENGINEERING - 38th cycle

THEMATIC Research Field: METHODOLOGIES FOR PROCESS AND CHARACTERIZATION OF COST-AFFORDABLE CERAMIC MATRIX COMPOSITES FOR AEROSPACE

Monthly net income of PhDscholarship (max 36 months)
€ 1400.0 In case of a change of the welfare rates during the three-year period, the amount could be modified.

Context of the research activity	
Motivation and objectives of the research in this field	Ceramic Matrix Composites (CMC) are a family of materials consisting of a refractory ceramic matrix toughened by long or short fibres, or particles. Composites based on Silicon Carbide toughened by carbon fibres (C/SiC composites) are a well-known solution for developing thermal protections, hot structures, and parts of propulsive systems in the aerospace field. The development of successful structural concepts in CMC materials depends crucially on their mechanical properties and costs since some of the possible production techniques require high investment in facilities or the use of expensive ceramic precursors and, in general, high energetical costs. Nowadays, the Liquid Silicon Infiltration (LSI) technique, developed a couple of decades ago (Krenkel, 2001), allowed a substantial reduction of manufacturing and energy cost of C/SiC CMC. Such technique is based on the pyrolysis of polymeric-matrix precursors and subsequent infiltrations with liquid silicon. It has been used extensively for the industrial production of carbo-ceramic brake disks. Recently, it has been qualified by ESA for the production of hot structures for space re-entry vehicles. LSI-C/SiC CMCs have a significant potential to produce cost-affordable and more sustainable CMC for lighter structures and more energetically efficient propulsive systems in the whole aerospace field. However, the full exploitation of such potential requires addressing some important issues. The objectives of the Ph.D. have been

	agreed upon between the Dept. of Aerospace Science and Technology of Politecnico di Milano (DAER) and Petroceramics S.p.A. A first objective consists in the experimental analysis and the formulation of predictive approaches related to the development of the defects and distortions during the phases of the LSI process. Such aspects complicate the production of complex parts and may require several technological trials, increasing economical and energy costs. Moreover, the micro-scale structures obtained in the process influence the strength and the non-linear response of the material. Accordingly, a second objective of the research is the analysis of the relations between the phenomena occurring in the LSI process and the final mechanical responses, to integrate them into a comprehensive modelling and characterization protocol, which is currently being developed at DAER, fundamental for the design of reliable and reusable hot structures.
Methods and techniques that will be developed and used to carry out the research	The research will be organized into three main segments, which will be supported by technological activities, experiments, and the development of numerical approaches. The key phases of the technological process and some experiments in the research segments will be carried out at Petroceramics S.p.A., and the student will spend periods of internship in the company, participating in the design, production of specimens, and to experimental activities. The first segment of the research will be focused on the pyrolysis phase of the LSI process. Technological experiments will be designed by varying the geometries considered and the process parameters. Thermo-mechanical numerical model at the meso-scale of the CMC laminates will be set up to simulate the shrinkage, the segmentation of fabric yarns, and the state of stresses involved in the transformation of the polymeric matrix. The numerical-experimental correlation will be carried out focusing on the pre-preg lay-up, the component shapes, distortion, and possible defects obtained after the pyrolysis. The second segment will be focused on the final phase of the LSI process, which is characterized by complex phenomena such as chemical interactions between fibre and matrix, the presence of

	unreacted silicon, microfractures occurring during the cooling phase, and residual stresses caused by the different coefficient of thermal expansion between fibre and matrix. Some of the specimens produced for the first phase will be infiltrated and subsequently tested for the evaluation of the mechanical response. The analyses of SEM micrography, taken on a set of specimens, will be used to develop linear and non-linear micro-scale models at the level of Representative Volume Elements. Such models will allow achieving a better insight into the effects of the microstructures originated by the aforementioned phenomena on the macroscopic response. In such phase, voxel-like meshes will be used for the development of models representing the details of the microstructures. Finally, the results achieved will be used to enhance the predictive capability of already existing non-linear models developed at the meso-scale level, which can be used to analyse the response at the level of structural details in the most critical zones of CMC components. The response of non-linear models will be correlated with the experimental results achieved in the second phase.
Educational objectives	The research activity will achieve significant educational objectives in different areas of the science of composite materials. From the technological point of view, the researcher will learn or refine the techniques for the production of polymeric matrix elements with different geometries. Moreover, she/he will participate in the implementation of the whole LSI process, including pyrolysis and infiltration. Her/his knowledge of such processes will be enhanced by the numerical activity performed at different modelling scales related to the technological phases. The researcher will conduct a series of experiments and measurements on different types of specimens, recording and analysing non-linear phenomena and damage development. Therefore she/he will acquire competencies in material characterization, including some basic skills regarding microscope analyses. Both the technological and experimental phases will be conducted in tight cooperation between industry and academia, thus providing a complete overview of research and development activities in the field of material

	science. From the numerical point of view, the researcher will develop finite element models both at the micro and macroscopic scale, by applying linear and non-linear analysis procedures. She/he will acquire competencies regarding composite material modelling and non-linear constitutive laws, including material properties dependent on temperature. The correlation with the experimental results will provide a significant experience relevant to the potential of modern computational tools, the capability to evaluate their limitations, and the importance of integration between numerical and experimental activities for the engineering application of advanced materials. Participation in a research project involving both high-level engineering and scientific aspects carried out within tight cooperation between industrial and academic institutions will also refine the communication skills of the researcher and her/his capability to interact with different types of working environments.
Job opportunities	The competencies acquired by the researcher will be valuable in all industrial fields where composite materials are used to develop lightweight and highly efficient structures. In the aeronautical field, polymeric matrix composites have become the primary choice for structures and the experience gained by the researcher in the lamination of polymeric precursors, management of complex technological processes, and numerical modelling of composites at different scales will represent a fundamental background for the design, analysis and production management of aeronautical parts. The specific and exhaustive knowledge of ceramic matrix composites (production, characterization, analysis) will open opportunities in all sectors involved in aerospace propulsion, including both jet and rocket engines, where these materials represent the more advanced solutions for parts such as nozzles and turbine blades. The development of thermal protection systems with structural capabilities also represents a central area of research for space applications, in particular for re-entry and reusable vehicles. The field of carbo-ceramic and carbon-carbon brake disks, both for automotive and aerospace applications, constitutes another important industrial

	sector where the specific competencies acquired in the research activity are fundamental. Finally, ceramic matrix composites also represent valuable solutions for developing ballistic protections. In all the aforementioned industrial and research fields, the combination of technological skills and structural competencies that characterizes the research activity here proposed represents a highly valuable quality, which is not easily available for industry and research institutions. Such aspect amplifies the job opportunities in the specific areas, but also provides a basis for careers requiring a broad vision of engineering problems related to the design and production of structures for the next generation of vehicles and buildings.
Composition of the research group	0 Full Professors 2 Associated Professors 1 Assistant Professors 3 PhD Students
Name of the research directors	Prof. Alessandro Airoldi

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Additional support - Financial aid per PhD student per year (gross amount)	
Housing - Foreign Students	--
Housing - Out-of-town residents (more than 80Km out of Milano)	--

Scholarship Increase for a period abroad	
Amount monthly	2100.0 €
By number of months	6

Additional information: educational activity, teaching assistantship, computer availability, desk availability, any other information
The Ph.D. candidate will receive a desk and a personal computer. Apart from the compulsory

ones, the Ph.D. candidate will have the opportunity to follow additional courses, receive economic support to attend summer schools, and participate in conferences. There will be the possibility of paid teaching assistantship.