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Significance and Need of Computational Analysis and Finite Element Modelling For the Investigation of Thermal Behaviour of Composite Materials

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ABSTRACT

Composite materials are the cutting edge materials that possess unrestrained opportunities for advanced material science and development. Thermal studies of composite materials are gaining greater impetus in the present scenario. This will help to comprehend the properties of materials as they change with temperature. The thermal characterization of hybrid composites has been progressively more important in a wide range of applications. The coefficient of thermal expansion, thermal conductivity, specific heat capacity, latent heat and thermal diffusivity are the most important properties of composite materials. Since nearly all composites are used in various temperature ranges, measurement of coefficient of thermal expansion (CTE) and thermal conductivity as a function of temperature is necessary in order to know the behaviour of the material. Thermal characterization and analysis of hybrid composites will depend on the factors that influence on the prominent thermo-physical properties presents a major challenge since they are sensitive to the type of reinforcement and method of manufacture. This research paper emphasizes the significance, need, applications and scope of computational investigation and finite element analysis of composite materials.

Keywords- *Composite materials, thermal studies, thermal characterization, coefficient of thermal expansion, thermal conductivity and computational investigation.*

I. INTRODUCTION

In present scenario, thermal characterization and analysis of composite materials have been gaining greater impetus. Thermal analysis of composites will help to comprehend the properties of materials as they change with temperature [1, 2]. The determination of thermal properties of composites is beneficial for the evaluation of thermal capacity, variation in the intensity of heat, heat diffusion and heat release rate. It has been customary to control the temperature in a predetermined way either by increase or decrease in temperature at a constant rate by the processes of linear heating or cooling. For aerospace and automotive applications, low coefficient of thermal expansion, high thermal conductivity and high electrical conductivity of composite materials are greatly beneficial. The thermal characterization and analysis of composite materials will depend on the factors that influence on the thermophysical properties. It is a major challenge since they are susceptible to the type of reinforcement and method of manufacture. The decisions based on the selection of materials for components are exposed to temperature variations and temperature gradients. Hence it requires the design engineer to have a lucid comprehension about the thermal responses and characterize the thermal properties of a wide variety of materials.

Thermal analysis is often used as a term for the study of heat transfer to evaluate specific heat capacity and thermal conductivity [2]. Thermal analysis of composite materials is essential to examine the thermal properties viz., conductivity, diffusivity, temperature potential, specific heat capacity, thermal expansivity, shock resistance, enthalpy, latent heat, displacement, stress, strain, thermal flux, thermal gradient and heat flow distribution.

In thermal analysis, a cluster of techniques and experimental procedures are available which are favourable for studying the thermophysical and kinetic properties of materials. Thermophysical properties can also be used for the characterization of composite materials to evaluate the properties of the matrix material that are essential for the thorough analysis of the composite [3]. The determination of thermal properties of composite materials is of utmost importance for the effective design and applications pertaining to aerospace and automotive engineering, electronic packaging, thermal management equipment, space science, electronics and instrumentation, heat sinks, thermal power and nuclear power engineering.

The need for thermal analysis of composites has to be discussed, as it finds engineering applications extensively. The behaviour of composite materials is often responsive to changes in temperature. This is because, the response of the matrix to an applied load is dependent on temperature and transformations in temperature. The variation in temperature can cause internal stresses and result in differential thermal expansion and contraction of the constituents [3]. The coefficients of thermal expansion of matrices and reinforcements are the function of temperature. The behaviour of the composites can be discussed in terms of size of the particle and thermally induced stresses developed as a result of the coefficient of thermal expansion between the reinforcement and the matrix.

A meticulous approach for thermal characterization and analysis of composite materials has to be accomplished for the present day applications. Thermal analysis includes test prediction, continuous validation tests and analysis. In the design and development of structures of aircraft, the major requirements viz., safety, cleanliness, costs based on production and manufacturing are the important issues for the fundamental decisions. Generally, the temperature field is also very important and is more pertinent for the assessment of stresses induced by thermal expansion. In the design process, the best method recommended is to acquire relevant thermal data by numerical simulations [4].

The major focus of computational investigation will lead to the development of numerical tools for the computational mesomodeling testing of materials. In the present scenario, the accessibility of the resources for the computational investigation and simulation techniques are beneficial to achieve speed and accuracy. In turn, it saves the development cost, production cost and computation time. Certain tools pertaining to simulation can save the development costs and is employed to validate the numerical methods by means of small scale materials for parameter identification. Hence it is necessary to focus on maximum effort for both experimentation and validation analyses. In computational modelling, homogenization has to be achieved mandatorily for the complete refinement of nodes. Also, meshing has to be accomplished by the selection of a particular element type. Homogenization is beneficial for the thorough analysis of materials. The prerequisite by using homogenization in the analysis of thermal properties is caused by a different selection of problems. Homogenization can be performed to abridge certain mechanisms and phenomena relating heat transfer by using specific tools of simulation. The application of homogenization to the properties of thermal material will facilitate to predict the profile of temperature of a structure. Any technique pertaining to thermal analysis of composites can be implemented and executed by using finite element method.

II. IMPORTANCE OF COMPUTATIONAL THERMAL ANALYSIS

The design of materials on the basis of numerical testing of microstructures can be comprehended for the distinct materials and microstructural characterization can be carried out systematically. To extend experimental information, the computational modelling on a variety of composite materials allows the fabrication of Aluminium matrix composites (AMCs) to be productive. For the analysis of AMCs, many researchers have suggested the analysis of unit cell of composite. Generally, there are complexities involved in computation to obtain reasonable results based on a small single unit owing to a lack of interaction between reinforcement and matrix. On the contrary, the computational investigation with multiple unit cells allows reliable results due to considerable material interaction [5]. Composite materials pose various challenges in computational modelling because of the nature and behaviour of materials. However, composite materials pose exceptional modelling challenges because of their different constituent materials, excellent properties and orientations. With the appropriate simulation tools, designers can predict performance, analyze reliability and potential failures, optimize construction, and export accurate information to manufacturing, all before a physical prototype is built.

Aluminium matrix composites have been constructive for industrial applications, such as aerospace and automotive engineering, due to its admirable thermal and mechanical properties. Finite element method (FEM) supplies an institutional investigation taking advantages of post-processes pertaining to graphical and mathematical approaches. It helps for systematic analysis of the behaviour of materials and associated properties, including the analysis of local stress and distribution of strain. Nevertheless, there are descriptive reports pertaining to the study of finite element analysis based on the thermal properties of Aluminium-Silicon

Carbide (Al-SiC) system. Finite element analysis (FEA) has been used extensively to simulate the thermal and mechanical behaviour of metal matrix composites. Aluminium has been acclaimed as a matrix material that possesses high CTE. Thus particles of Silicon Carbide in Aluminium matrix have been considered as a role of CTE reduction in Al-SiC system. The inferences for the different solutions pertaining to finite element analysis for the classifications of composites can be compared with the results of mathematical models and with the experimental investigation. Computational simulations on the thermal analysis of metal matrix composites comprises Aluminium and Silicon Carbide which can be analyzed by considering the volume fraction of Silicon Carbide [6, 7, 8].

Generally, the research can be focused on computational thermal analysis of hybrid composites. ANSYS is the commercially available computational fluid dynamics (CFD) package used to carry out computational thermal analysis of composites. In computational or numerical investigation, it is essential to emphasize the mode of computation, element type, type of characterization, selection of nodes and the pertinent boundary conditions. The experimental values can be used as the prominent material properties and the computational investigation can be accomplished for the determination of thermal properties viz., thermal displacement, thermal stresses, thermal and mechanical strain, thermal flux, thermal gradient and rate of heat flow. To validate the results obtained computationally, theoretical modelling can be accomplished. Eventually, a comparative study can be carried out to validate the computational and theoretical results. In the computational investigation of composites, mesh independence studies or numerical convergence test has to be accomplished [5]. In computational analysis, numerical convergence or mesh independence study is extremely important to reduce the cost of computation and maintain utmost accuracy in the results.

III. FINITE ELEMENT MODELLING

Computational or numerical investigation can be carried out for the characterization of mechanical and thermal behaviour of composite materials comprehensively. Generally, it is accomplished by using finite element approach. In the finite element approach concerning engineering problems, the imperative tasks for the generation of mesh, numerical processing, graphical representation of results and interpretations are allocated to computer programs independently. The computer programs can be embedded under a common interface to enable the user to interact with all segments in a single environment. They can also be implemented as separate sections by using a software package. In numerical investigation, discretization is an important step that helps in simplifying the computational procedure and is beneficial to ensure the validity of the numerical solution by convergence test. Discretization of the solution domain into an appropriate computational mesh is the basic step in the finite element simulation. The important factors in the selection of a specific mesh design are domain geometry, type of finite elements, accuracy and cost of computation. The accuracy of the computational solutions depend on consistency of the mesh with the geometry of the domain, nature of the solution sought, type of elements selected and aspect ratio [9].

The computational finite element modelling on a variety of composite materials allows the fabrication of composite materials to be productive based on experimental information. For the analysis of composites, numerous researchers have suggested the analysis of unit cell of a composite. Generally, there are computational difficulties to obtain sensible results based on a small single unit owing to a lack of interaction between reinforcement and matrix. On the contrary, the computation with multiple unit cells allows consistent results due to considerable material interaction [9, 10, 11, 12, 13, 14, 15].

Finite element method is regarded as an efficient technique for the prediction and computation of the properties based on mechanical and thermal behaviour of composite materials. A flourishing application of metal matrix composites in the topic of engineering design necessitates an elaborate categorization of mechanical and thermal properties. The properties based on thermal expansion of composite materials play a significant role in computing the thermal properties viz., thermal displacement, thermal strain and thermal stresses in components or structures of composites. Analogously, the properties based on the thermal conductivity behaviour of composite materials play a dominating role for the computation of thermal gradient, thermal flux and heat flow. The numerous monotonous factors in the process of characterization of materials have led a systematic way to several numerical and analytical techniques [16, 17, 18, 19, 20, 21].

The main objective in carrying out computational thermal analysis is to determine the temperatures and heat distribution on the prominent nodes in both the matrix and reinforcements. The computational investigation can be accomplished to determine the thermal properties viz., thermal displacement, thermal strain and thermal stress based on thermal expansion behaviour of hybrid composites. Correspondingly, the computational thermal properties viz., thermal gradient, thermal flux and rate of heat flow can be computed based on thermal conductivity behaviour of composites. Numerical convergence test or mesh independence studies has been carried out. A comparative study can be carried out to corroborate numerical and analytical results.

In computational investigation of composite materials, numerical convergence test or mesh independence studies has to be carried out mandatorily. Numerical convergence or mesh independence study is essential to reduce the cost of computation and maintain extreme accuracy in the results based on computational analysis [18, 19, 20, 21, 22]. It is essential to check the validity and accuracy of the numerical or computational solution. This test depicts the computation of the numerical solution on successively finer grids. Mesh independence leads to extreme accuracy in the computational solution after finer mesh refinement is attained. Also, there will not be any substantial variation in the numerical solution after finer mesh refinement. Numerical convergence can be accomplished depending on the various element distributions. The experimental values of thermal expansion and thermal conductivity can be used as the material properties for the computation of thermal properties viz., thermal displacement, thermal stress, thermal strain, thermal gradient, thermal flux and rate of heat flow of hybrid composites. These thermal properties can be compared with the theoretical results to check for the validity of the numerical solution.

IV. COMPUTATIONAL MODELLING SOLVERS

Finite element method identifies a broad spectrum of techniques. Two predominant classifications are FEM formulation and FEM solution. FEM formulation involves displacement, equilibrium, mixed and hybrid methods, whereas FEM Solution involves stiffness, flexibility and mixed method. But emphasis has been given to displacement formulation and stiffness solution. This combination is referred to as Direct Stiffness Method (DSM). Practically all finite element codes are based on DSM and the computer implementation can be carried out comprehensively.

The prominent direct solvers that have been used for computational modelling are sparse direct solver, frontal solver, and a wider choice of iterative solvers. Sparse direct solver utilizes the finite element matrices that are normally sparsely populated. This sparseness allows the system of simultaneous equations to be solved efficiently by minimizing the operation counts. On the contrary, frontal solver is designed to minimize the memory used in the solution process although the operation count is generally more than that of the sparse direct solver. The sparse direct solver is the useful solver for all analyses, except for electromagnetic analyses that includes both polynomial elements and constraint equations, spectrum analyses, and sub-structuring analyses. For nonlinear problems, the sparse direct solver provides robust solution with good performance of the central processing unit, usually faster than the frontal solver.

In frontal (or wavefront) solution, the number of equations that are active after any elements have been processed during the solution procedure is referred to as the wavefront at that point. This method is beneficial for placing a wavefront restriction on the problem definition, which depends upon the amount of memory available for a given problem. Wavefront limits tend to be restrictive only for the analysis of arbitrary three-dimensional solids. In the wavefront procedure, the sequence in which the elements are processed in the solver is crucial to minimize the size of the wavefront.

Computational modelling of composite materials is generally governed by mass, momentum and energy conservation equations. The mass and momentum equations are related to the constituent volume fraction and density of composite materials. It is recognized that, the weight fraction condition of composites is a direct consequence of relative motion between the constituents. Energy conservation equation relates the energy and heat transfer processes pertaining to the thermal characterization of composites.

The structural and thermal analyses comprise four main steps viz., build the model, apply loads & obtain the solution, analyze the computational elements and review the results. The main computational aspects that have been considered in structural and thermal analyses of hybrid composites are the mode of computation, element type, material properties, type of model, method of meshing, boundary conditions, convergence test analysis, and review of results. To explore the thermal expansion behaviour of hybrid composites, the mode of computation that can be used is ‘structural’ and element type is ‘Solid’ Brick 8node 45. The pertinent material properties that can be considered are density, moduli of elasticity, Poisson ratio and thermal expansion for the recommended temperature ranging. The thermal properties viz., thermal displacement, thermal strain and thermal stress can be investigated based on thermal expansion behaviour of composites. Analogously, to explore the thermal conductivity behaviour of hybrid composites, the mode of computation that can be used is ‘thermal’ and element type selected is Solid Brick 8node 70. The material properties that can be considered are thermal conductivity, density, specific heat capacity and enthalpy for the suggested temperature range. For both computational conditions, temperature boundary condition has to be adopted. The thermal properties viz., thermal gradient, thermal flux and rate of heat flow can be investigated based on thermal conductivity behaviour of hybrid composites. Mesh independence or numerical convergence test has to be accomplished for a particular specimen, if the sample size is same, based on thermal expansion and thermal conductivity behaviour of hybrid composites.

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