Polymer Science and Technology

Fatigue of Polymer Matrix Composites at Elevated Temperatures

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PREFACE

In recent years, advanced composite materials have been frequently selected for aerospace applications due to their light weight and high strength. Polymer matrix composite (PMC) materials have also been increasingly considered for use in elevated temperature applications, such as supersonic vehicle airframes and propulsion system components. A new generation of high glass-transition temperature polymers has enabled this development to materialize. Clearly, there is a requirement to better understand the mechanical behaviour of this class of composite materials in order to achieve widespread acceptance in practical applications. More specifically, an improved understanding of the behaviour of PMC materials when subjected to elevated temperature cyclic loading is warranted.

This book contains a comprehensive review of the experimental and numerical studies conducted on various PMC materials subjected to elevated temperature fatigue loading. The experimental investigations typically focus on observing damage phenomenon and time-dependent material behaviour exhibited during elevated temperature testing, whereas insufficient fatigue test data is found in the literature. This is mainly due to the long-term high temperature limitations of most conventional PMC materials and of the limitations on the experimental apparatus. Moreover, it has been found that few fatigue models have been developed that are suitable for damage progression simulations of PMC materials during elevated temperature fatigue loading. In general fatigue damage simulation models for PMC materials are quite complex due to the nature of the heterogeneous microstructure of these advanced materials. Adding the element of elevated temperature further complicates the physics of the problem due to the probable time-dependent behaviour of the material and the potential effects of aging. Although this review is not exhaustive, the noteworthy results and

the trends of the most important studies are presented as well as their apparent shortcomings. Recommendations for future studies are also briefly addressed and the focus of some current research efforts is outlined.

CONTENTS

Chapter 1

INTRODUCTION

Considerable progress in the development of composite materials during the past few decades has enabled their widespread utilization for various industrial and recreational applications. In recent years advanced composites have emerged as indispensable materials in the aerospace industry, and as a consequence are more frequently employed due to their high strength-to-weight ratios when compared to conventional metallic components. This is exemplified by considering modern commercial aircraft such as the Airbus A380 and the Boeing 787, both of which utilize composite materials for primary structural load bearing components. The airframe of the A380 that is currently in service is comprised of more than 20% composite materials [1], mainly located in the wingbox interior structure and the aft fuselage section. Once completed, the 787 airframe will have a gross weight that is comprised of approximately 50% composite materials, which results in an aircraft that is 80% composite by volume [2]. The established acceptance of these materials in the aircraft industry and their importance for the future development of more efficient aircraft is apparent.

The integration of composite materials into the propulsion systems of modern commercial and military aircraft has not experienced the same advancement. This is mainly due to the demanding temperature regime that engine components must withstand during standard operation. Nevertheless, there has been some success in using composite materials to manufacture engine components. In the mid-1990's GE successfully integrated polymer matrix composite (PMC) fan blades on the GE90 turbofan engine. Currently GE is developing the next generation turbofan engine GEnx, which comprises of composite fan blades and an entire fan casing manufactured from a braided carbon-fiber PMC material [3]. Since these components are in the cold section of the engine, the ambient operating temperature is typically less-than 100°C. In addition, ceramic-matrix composites (CMC) and metal-matrix composites (MMC) are currently being considered as materials for jet engine components due to their superior heat resistance capabilities. Pratt and Whitney have considered a CMC material for the seals on the exhaust nozzle of the F100 PW 229 military turbine engine, while GE are considering a CMC material for the turbine vanes in the F136 developmental engine. These components are in the hot section of the engine, which can reach temperatures well in excess of 500°C. Clearly, PMC materials would not withstand long-term exposure to this severe temperature environment.

There are however current demands in the industry to manufacture various structural components from composite materials for employment in the moderate temperature regions of jet engines [4], and for next-generation supersonic aircraft fuselage structures [5]. These applications demand long-term exposure to operating temperatures in the 150 - 350°C range. Fiber-reinforced PMC materials with high temperature resins may be suitable candidates for these applications, which will provide weight-saving advantages over conventional metallic components and a reduction in manufacturing costs when compared to MMC and CMC components. A new generation of high glass-transition (T_g) temperature polymers has enabled the current development of high temperature PMC materials. Consequently, high temperature PMC's have been the focus of numerous research efforts over the past 2 decades. Both experimental and numerical studies have attempted to predict and understand the mechanical behaviour and the durability of PMC's at elevated temperatures. More specifically, few fatigue studies on these advanced materials have been presented in the literature. Understanding the fatigue behaviour of advanced composite materials is crucial for predicting their fatigue life and durability. Since aircraft components may be required to survive for over 20 years in service, the accuracy of fatigue life prediction is necessary to ensure the safe-life of composite components.

Chapter 2

FATIGUE BEHAVIOUR OF PMC MATERIALS

Continuous unidirectional, woven or braided fiber-reinforced PMC laminates are commonly used in critical aircraft structural parts. These materials are inhomogeneous and anisotropic, and as such exhibit markedly different behaviour than homogeneous and isotropic materials such as metallic alloys. It is therefore difficult to predict the fatigue properties of these composite materials.

In general, the fatigue behaviour of metallic alloys is well understood and rather predictable. Components made from metals typically exhibit fatigue micro-crack initiation at high stress concentration locations. The gradual growth of these micro-cracks progresses for most of the components lifetime, having little influence on the macroscopic properties of the material. During the final stage, the cracks coalesce to form a larger crack which leads to rapid final failure. Once the visible dominant crack is formed, after a certain number of load cycles, the fatigue life can be determined as long as the initial crack size and its growth behaviour are known. For metallic alloys the macroscopic material properties such as stiffness and strength are unaffected or only slightly affected during fatigue loading, thus simple linearly elastic fracture mechanics models are often adopted to simulate fatigue crack propagation.

Composite components on the other hand exhibit widespread damage throughout the structure without any explicit stress concentrations. Damage can also exist on both microscopic and macroscopic size scales. The common forms of damage (i.e., damage mechanisms) caused by cyclic loading are matrix cracking, fiber fracture, fiber-matrix interface debonding and delamination between adjacent plies [6]. The interaction of these damage mechanisms has been experimentally observed to have a significant influence on the fatigue behaviour [7]. Also since damage commences after only a few loading cycles and progresses upon further cycling, there is typically a gradual stiffness loss in the damaged areas of the material which leads to a continuous redistribution of stress during cyclic loading. As a consequence, simple fracture mechanics-based models are not suitable for composites since the aforementioned damage mechanisms are quite complex and the relationship between stress and strain is no longer linear. In addition, some types of composites such as cross-ply laminates have been found during cyclic loading to reach a state of damage equilibrium, which is deemed a characteristic damage state (CDS) [8]. The progression of matrix cracks in the cross-plies was found to arrest at ply interfaces and at fiber locations, causing the degradation of stiffness to vanish. Therefore, accurate prediction of composite component fatigue behaviour and fatigue life is a complex task.

Experimental characterization of composites is also difficult due to the challenges in inspecting the aforementioned forms of damage and in measuring the continuous degradation of macroscopic material properties. Factors such as the constituent material properties, the fiber structure (unidirectional, woven, or braided), the laminate stacking sequence, the environmental conditions and the loading conditions (maximum stress, loading frequency) among others influence the fatigue behaviour of composites. This results in laborious and costly experimental programs to characterize the material and to generate sufficient fatigue life data. This further limits the approval of newly developed prediction models since validation of a robust model must be done using various experimental test results.

High temperature exposure during cyclic mechanical loading undoubtedly augments the material behaviour and the progression of the aforementioned damage mechanisms due to the potentially complex thermo-mechanical interactions. Additional property degradation mechanisms such as physical and chemical aging may continuously alter the composite properties with time, specifically impacting the polymer matrix behaviour. The influence of the time-dependent material behaviour on the fatigue damage mechanisms will also be significant at severe operating temperatures. This may in fact be the case at temperatures well below the T_g of the polymer matrix [9]. Development of a comprehensive prediction methodology for fatigue behaviour or fatigue life prediction at elevated temperatures is consequently an even more difficult task. Moreover, long-term fatigue testing at elevated temperatures poses additional difficulties due to the severe test environment, which may limit utilization of conventional fatigue testing equipment and techniques. As indicated, the continued development of high temperature polymers and their respective composites has enabled this state-of-the-art research to persist on these advanced materials.

Chapter 3

Development of High Temperature Polymers

For a number of decades now, many researchers have considered the effects of elevated temperature exposure on various polymers. In the 1970's and 1980's, a number of high temperature polymer resins were developed by NASA as part of a larger research effort and considered as potential candidates for fiber-reinforced composite materials. Through this research, two groups of polymers known as linear polyimides and addition aromatic polyimides were developed [10]. The linear polyimides are attractive since they are both tough (i.e., high damage tolerability) and have remarkable thermal stability over a wide temperature range. The addition aromatic polyimides are more brittle, but have highly cross-linked molecular structure [11], which is beneficial for higher temperature stability where linear polyimides may fail. The main setback with these types of polyimides is that they contain known carcinogenic by-products and are very hazardous, which poses many manufacturing difficulties and risks.

The first group of elevated temperature polyimide resins widely produced by NASA for use in fiber-reinforced composites was developed using a polymerization of monomer reactants (PMR) approach [12]. These addition-type polyimides were developed to have excellent thermal stability, ease of manufacturability and the ability to withstand temperatures in excess of 300°C (i.e., a trade-off between linear and addition aromatic polyimides). The static strength of these polyimides over long-term high temperature exposure was found to be fairly stable. The main derivative of this group of polyimide resins to be employed for high temperature aerospace applications is PMR-15. Many studies were conducted by NASA to improve the manufacturability and mechanical performance of PMR-15, and to 'tailormake' this polyimide resin for use in fiber-reinforced composites [13]-[15]. Experimental studies were later conducted on fiber-reinforced PMR-15 composites [4]. The static mechanical property degradation, weight-loss, coupon dimensional changes, and surface thermal oxidation effects due to long-term aging at elevated temperatures were all considered during testing. Aging temperatures were limited to 350°C. Surface thermal oxidation was believed to be a significant contributor to material property degradation for aging greater-than 100 hours, causing microvoids and microcracks to initiate just below the damaged material surface layer. Although testing has been conducted at higher temperatures for PMR-15 composites, the maximum useful long-term operating temperature is approximately 260°C for jet engine applications.

Due to the successful development and wide regard of PMR-15, additional polyimide resins were subsequently developed for high temperature composite applications. NASA also developed AMB-21 [16] and DMBZ-15 [17] high temperature polymers. These thermoset polyimides have similar properties and temperature capabilities as PMR-15, but without the hazardous carcinogenic compounds. In fact DMBZ-15 has a higher wear resistance and a slightly higher T_g when compared to PMR-15, which makes it suitable for long-term exposure at temperatures >300°C. Moreover, Dupont developed a thermoplastic polyimide Avimid K3B, which has been considered for supersonic transport aircraft [18]. The continuous maximum operating temperature for K3B is approximately 180°C. A number of additional thermoset and thermoplastic polyimide resins such as R1-16, PETI-5 and PIXA among others have also been considered for PMC components on supersonic aircraft with the same temperature limitations [5]. Finally, a number of high temperature BMI polymers have been developed and used in the industry. Common BMI polymers include 5250 and 5260 developed by Cytec Engineered Materials, as well as F655-2 developed by Hexcel Corporation. These polymers have a continuous maximum operating temperature of approximately 150°C.

Although a number of high temperature polymers and their respective fiber-reinforced composites have been developed, there has been little use of these materials in high temperature load bearing applications. Additionally as already indicated, few studies have been conducted that consider the fatigue behaviour of these PMC materials at elevated temperatures.

Chapter 4

REVIEW OF ELEVATED TEMPERATURE FATIGUE STUDIES

This review aims to chronologically delineate the most important accomplished fatigue studies on high temperature PMC materials. First, a discussion of the high temperature experimental work conducted on these advanced materials will be presented. This is followed by a presentation of the subsequently conducted numerical studies.

4.1. EXPERIMENTAL

Most experimental studies focus on temperature-dependent material property degradation during static loading or isothermal aging test conditions. There are few experimental studies that consider fatigue loading at elevated temperatures. These studies will be presented, and the focus of the discussion will be on the indicated observable effects of time and temperature on the fatigue behaviour and corresponding damage mechanisms. The discussion will also include detail of the experimental test protocol and test equipment for specific studies.

Lo et al [19] developed a fiber-reinforced composite which was manufactured with CSPI, a modified polyimide developed at the Chung Shan Institute of Science and Technology, having a T_g of 511°C. Isothermal mechanical fatigue testing of carbon fiber/CSPI and carbon fiber/PMR-15 composites at 450°C was conducted using unidirectional and [0/90/±45] laminates. For a peak fatigue stress level of 60% of the ultimate strength and a loading frequency of 2 Hz, it was found that the fatigue life at room