Research Progress of Continuous Fiber Reinforced Ceramic Matrix Composite in Hot Section Components of Aero engine

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Abstract: Continuous fiber reinforced ceramic matrix composite (CFRC CMC) possessed low density, high temperature resistance, high strength and high toughness, which have been identified as a key and promising material for replacing the traditional super alloy. CFRC CMC had been used in some hot section components, such as nozzle, combustor and turbine stator on M88-2, F100-PW-229, CFM56-5B, F-135, GEnx, LEAP-X and other aeroengines. Manufacturing technologies of CFRC CMC were thought as the commanding elevation for hot section components of aeroengines, and therefore much attention was given in Europe, America, Russia and other developed countries and regions. The evaluation and application of CFRC CMC were introduced in detail. Further, the challenge and tendency in the future were also put forward in this study.

1. Introduction

With the increase of thrust-to-weight ratio of aero engine, nozzle, combustor, turbine components and other hot section components suffer more serious heat flux and impact load; for instance, the turbine inlet temperature reaches 1500°C with thrust-to-weight ratio of 10, and the turbine inlet temperature will increase to 1800°C when the thrust-to-weight ratio among 12-15. Therefore, the harsh service conditions may produce extensive cracking and excessive creep deformation in the traditional super alloy, which means the traditional super alloy is hard to satisfy the request of high temperature components shown in Figure 1. Further, low fuel consumption and long lifetime are the most critical factors to the reduction of operating cost and the improvement of flying reliability for civil aircraft. An important way to realize the achievement mentioned above is the improvement of aero engine technology, particularly the application of advanced high temperature materials. So, advanced high temperature materials with low density, high temperature, high strength and long lifetime have attracted much attention and become a research focus for many governments, research organizations and aero engine manufacturers [1-3].

Continuous fiber reinforced ceramic matrix composite(CFRC CMC), such as carbon fiber reinforced ceramic matrix composite (C/SiC CMC) and silicon carbide fiber reinforced ceramic matrix composite (SiC/SiC CMC), possessed low density among 2-3g/cm³ and high temperature resistance up to 1600°C compared with superalloys, and higher fracture toughness compared with monolithic ceramics [4-6]. For that reason, CFRC CMC has been identified as a key and promising material to meet these requirements for hot section components of aero engine in general, which could improve the service temperature by 200-350°C, reduce or even replace the cooling structure and cooling medium, and enhance the reliability of aero engine effectively [7,8].
Tremendous manpower and resources of numerous government, research institutes and major engine manufacturers have been spent occupying the commanding elevation of advanced technique represented by CFRC CMC. Two companies for SiC/SiC CMC prepregs and SiC fiber would be completed in 2018 and 2019 in Alabama, U.S.A, and would provide SiC/SiC CMC raw materials up to 20 tons a year to United States Department of Defense, United States Department of energy, GE, SAFRAN and other corporations admitted by U.S. Law. In addition, NGS company was set up by Nippon Carbon Company, GE and SAFRAN in 2012 in Toyama of Japan, which specialized in producing Nicalon SiC fibers to meet the growing demand for SiC/SiC CMC.

The application of CFRC CMC followed the rules from stationary to rotational components, from middle to high temperature and load. Firstly, the environmental tests of stationary components of middle temperature and middle load were carried out on the experiment platform and aero engine in service, such as nozzle seals and flaps. Secondly, stationary components of high temperature and middle load, such as combustor tube, flame holder, turbine outer ring and turbine guide vane, are also tested accordingly. Lastly, rotational components with high temperature and load, such as turbine rotors, are also in urgent need of research depending on certain particular tester.

2. Rotational components with middle temperature and load such as nozzle seals and flaps

C/SiC and SiC/SiC CMCs were prepared and tested by SNECMA based on the requirement of hot section components with high temperature and low density. SiC/SiC CMC named SEPCARBINOXR A262 system and C/SiC CMC named SEPCARBINOXR A262 system were manufactured in the 1980s, and the latter was applied successfully as divergent flaps in M88-2 aero engine in 1996(Figure 2), which marked the first application of CMC in hot section components of aero engine. Furthermore, in order to solve component changes and structural damage due to the oxidation of ceramic matrix and silicon carbide fiber, new material systems named SEPCARBINOXRA500 C/SiC CMC and CERASEPR A410 SiC/SiC CMC were manufactured. Six seals with two different cross-sections for the F100-PW-229 powered F15 fighters were made(Figure 3) : two variable cross-section seals with A410 SiC/SiC CMC system , two constant cross-section seals with A410 SiC/SiC CMC system and two seals with A500 SiC/SiC CMC system. Then the different seals mentioned above were placed on
the engine test platform, and suffered between 4600 and 6000 total accumulated cycles including 1300 to 1750 engine operating hours, which was superior to the traditional super alloy components [9-12].

Figure 2. CMC divergent flaps in M88-2 aero engine.

Figure 3. CMC seals in F100-PW-229 aero engine.

CMC was identified as the most promising candidate material for hot section components of aero engine and has been concerned highly and supported vigorously in America since 1980s [13]. CFRC CMC-related projects included HITEMP(Advanced High Temperature Engine Materials Technology), IHPTET (Integrated High Performance Turbine Engine Technology), UEET(Ultra Efficient Engine Technology) and VAATE (Versatile Affordable Advanced Turbine Engines). CMC seals and flaps produced by NASA and GE were applied successfully in F100, F414 and F110 aero engine, which benefited much from these research projects, especially the IHPTET project. CFRC CMC exhaust nozzles prepared by PW have been applied in F119 aero engine powered F22 fighters (Figure 4) and F135 aero engine powered F35 fighter(Figure 5), which lead to reduction of weight, improvement of performance and extension of service life obviously. In addition, CFRC CMC exhaust nozzles prepared by GE and SAFRAN showed good performance after ground testing, and successfully
applied in CFM56-5B aero engine powered A320 aircraft, which marks the first commercial application of CFRC CMC in aero engine(Figure 6) [14-20].

Figure 4. CFRC CMC exhaust nozzles in F119 aero engine.

Figure 5. CFRC CMC exhaust nozzles in F135 aero engine.
2.1. Stationary components with high temperature and middle load such as flame holder, turbine outer ring and turbine guide vane

Stationary components with high temperature and middle load were studied in America and Europe almost instantaneously. In 1990s, SiC/SiC CMC combustor liner and flame holder were researched and manufactured successfully by SNECMA. In particular, the former had suffered 600 engine test cycles including total accumulated cycles of 100 hours, and the latter also showed excellent performance through engine test of 143 hours at 1180°C (Figure 7). Moreover, the performance experiment and combustor environmental simulation tests demonstrated that SiC/SiC CMC flame tube and combustor liner with environmental barrier coating possessed high temperature stability with service life up to 5000 hours at 1200°C in IHPTET project. Both the stability and practicability of SiC/SiC CMC flame tube were also proved on XTE65/2 demonstrator supported by JTAGG (Joint Turbine Advanced Gas Generator) project, which kept in good condition at flame tube wall temperature of 1480°C (Figure 8) [21-23].
SiC/SiC CMC turbine guide vane manufactured by NASA Glenn research center effectively reduced the cooling air flow by 15%~25% and passed the simulation tests successfully with flow velocity of 60m/s, environmental pressure of 6 atmospheres and test temperature of 1200°C at the exit of the combustor. As shown in Figure 9, SiC/SiC CMC turbine guide vane and superalloy turbine guide vane were installed in the hot environmental test equipment respectively [24,25]. The superalloy turbine guide sustained severe ablation; on the contrary, no obvious degradation of SiC/SiC CMC turbine guide vane appeared after 110 cycles which meant that SiC/SiC CMC possessed more excellent shock resistance and ablation resistance as turbine guide vane than super alloy. Third stage low pressure turbine guide vanes were manufactured with CFRC CMC by G E and R·R, and was tested on F136 aero engine altitude test bench, the candidate engine powered F35 fighter (Figure 10). Aeroengine test showed that CFRC CMC low pressure turbine guide vane could endure gas temperature up to 1200°C and reduce the cooling air flow by 50%.
In addition, SiC/SiC CMC flame tube, combustor liner, first stage high pressure turbine shroud ring and second stage turbine guide vane were developed and tested on GEnx high bypass ratio engine demonstrator for more than 350 cycles in 2015 (Figure 10). The first round of ground test was accomplished in October 2016, and SiC/SiC CMC components mentioned above will be applied directly to GEnx aero engine. High pressure turbine shroud rings of LEAP-X series engine were successfully manufactured with CFRC CMC by GE leading to the improvement of efficiency and decrease of weight for high pressure turbine significantly (Figure 12) [26]. LEAP-1A aero engine made a successful maiden flight on A 320 aircraft in May 2015, and was accredited by FAA (Federal Aviation Administration) and EASA (European Aviation Safety Agency), which would mark the first major use of CFRC CMC. GE are fully confident about the future development of CFRC CMC on aero engine and will apply CFRC CMC as both stationary components and rotational components in the next generation military aero engine supported by AETD (Adaptive Engine Technology Development) project.
Figure 11. Photograph of F136 aero engine.

Figure 12. Photograph of Leap-X aero engine.

Figure 13. SiC/SiC CMC turbine outer ring and turbine guide vane manufactured.

The Japanese government launched AMG (Advanced Material Gas-generator) project and ESPR (Research and Development of Environmentally Compatible Propulsion System for Next-generation Supersonic Transport) project in 1990s. With the support of these projects mentioned above, SiC/SiC CMC turbine outer ring and SiC/SiC CMC turbine guide vane were manufactured and tested on high temperature core engine (Fig 13). SiC/SiC CMC turbine outer ring kept in good condition with no crack and ablation at 1650°C for 20 hours, and SiC/SiC CMC turbine guide vane maintained excellent structural stability and durability under high temperature gas at temperature among 1150 ~ 1300°C for 1000 cycles [27,28].

3. Rotational components with high temperature and high load such as turbine rotor
Turbine rotor was typical high temperature and high load component, and suffered worst heat flux and impact load in service. CFRC CMC possessed low density, high temperature resistance and excellent oxidation resistance, which favors the reduction of cooling structure and improvement of the efficiency and of aero engine. CFRC CMC turbine rotors have been manufactured due to the effort of researchers in many countries. High temperature resistance and durability test of SiC/SiC CMC turbine rotor blade manufactured by GE were successfully performed and confirmed on F414 aero engine for more than 500 hours in 2015, which was the first round of ground test for CFRC CMC turbine rotor. The ground test mentioned above was a milestone in the development of CFRC CMC, and greatly expanded the application field of CFRC CMC. In addition, Rolls Royce considered CFRC CMC as one of the key technologies for reducing the fuel consumption and improving the
performance of aero engine. In order to improve the manufacturing technology, Rolls Royce acquired one CFRC CMC producer and planned to estimate and test high pressure turbine blade in EFE (Environmentally Friendly Engine) project[29][30].

4. Domestic research status and challenges of CFRC CMC
With almost thirty years of development, material properties and preparation process of CFRC CMC have acquired great progress represented by Avic Composite Corporation, Northwestern Polytechnical University and National University of Defense Technology. Although the basic properties of CFRC CMC has approached the international standard, there are obvious margins in life test and engineering application compared with the developed country. So we are badly in need of planned and systematic research of CFRC CMC hot section components for military or civilian aero engine. In order to fulfil object above, the following problems need to be solved.

4.1. Establish design criteria of hot section components based on the CFRC CMC’s characteristics
The traditional design principle and model no longer applies for the essential differences between CFRC CMC and superalloy. So, it is highly necessary to study the preform, matrix, interphase and surface coating from multi level and multi scale, and establish the CFRC CMC design criteria.

4.2. Enhance research of failure mechanism and life prediction model of CFRC CMC
Failure mechanism is an important component for the application of CFRC CMC in hot section component. The decline of properties and the damage of structure might led to component deformation, even failure of the aero engine. So, much attention should been paid to the damage and failure mechanism of CFRC CMC, and then evaluation and prediction of CFRC CMC’s service life could be achieved through theoretical analysis and experimental research.

4.3. Break through the key technologies during the whole industry chain of CFRC CMC manufacture
The research and development of CFRC CMC component involves considerable production processes such as preparation of raw materials, weave of fiber preform, densification of ceramic matrix, precision machining of CFRC CMC body, assembly of CFRC CMC component and so on, and a comprehensive breakthrough for all the production processes mentioned above is needed which would promote the development of CFRC CMC hot section component of aero engine effectively.

5. Conclusion
In this paper, the applications of continuous fiber reinforced ceramic matrix composites (CFRC CMCs) in hot section components of aero engine are discussed. The application of CFRC CMC followed the rules from stationary to rotational components, from middle to high temperature and load. The evaluation and application of CFRC CMC were introduced in middle temperature and middle load components such as nozzles, high temperature and middle load stationary components such as combustor tube, flame holder, turbine outer ring and turbine guide vane and rotational components with high temperature and load such as turbine rotors in detail. Further, the challenge and tendency in the future are also put forward in this study.

References
[1] Naslain R 2004 Composites Science and Technology 64 155
[2] Evans A G, Marshall D B 1989 Acta Materialia 37 2567
[3] Chen M W, Qiu H P, Jiao J 2013 Key Engineering Materials 544 43
[4] Hisaichi O, Shoju M, Masakazu O 1999 Composites A 30 489
[5] Ganesh A S, Raja S M 2011 Journal of the European Ceramic Society 31 1145
[6] Voorde M H, Nedel M R 1996 Ceramic Engineering and Science Proceedings 17 3
[7] Yoshida K 2010 Journal of the Ceramic Society of Japan 118 89
[8] Ding D H, Zhou W C, Luo F 2012 Ceramics International 38 3929
[9] Kerams R J, Hay R S, Parthasarathy T A 2002 Journal of the American Ceramic Society 85 2599
[10] Bouillon E P, Sprriet P C, Habarou G 2003. Engine test experience and characterization of self sealing ceramic matrix composites for nozzle application in gas turbine engines. Proceedings of AMSE Turbo EXPO, Atlanta, Georgia, USA.
[11] Christin F 2001. Design, fabrication and application of C/C, C/SiC and SiC/SiC composites. In: KRENKEL W ed. High Temperature Ceramic Matrix Composites. Weinheim: WILEY-VCH Press, 731.
[12] Qiu H P, Chen M W, Xie W J 2015 Aeronautical Manufacturing Technology 14 94
[13] Pierce JL, Zawada L P, Srinivasan R 2003 Journal of Materials Engineering and Performance 12 354
[14] Nakano K, Sasaki K, Saka H 1995 Ceram Trans. 58 215
[15] Viars P R The impact of IHPTET on the engine/aircraft system integrated high performance turbine engine technology. AIAA-89 2137
[16] Liang C H, Liu H X, Sun M X 2014 Development and key technologies of US variable cycle engine. Shenyang: AVIC Shenyang Engine Design and Research Institute.
[17] Halbig M C, Jaskowiak M H, Kiser J D 2013. Evaluation of ceramic matrix composite technology for aircraft turbine engine applications Washington: AIAA
[18] Lacombe A, Sprriet P, Allaria A, 2009 Ceramic Matrix Composites to make breakthroughs in aircraft engine performance 50th AIAA/ASME/ASCE/AHS Structures, Structural Dynamics, and Materials Conference, California
[19] Murthy P, Nemeth N, Brewer D 2008 Composites B 39 694
[20] Verrilli M, Calomino A, Thomas D J 2004 Characterization of ceramic matrix composite vane subelements subjected to rig testing in a gas turbine environment 5th International Conference on High-Temperature Ceramic Matrix Composites
[21] Dicarlo J A, Roode M V 2006. Ceramic Composite Development for Gas Turbine Engine Hot Section Components American Society of Mechanical Engineers
[22] Li L B 2016 Materials 9 62
[23] Kim D P, Cofer C G 1995 Journal of the American Ceramic Society 78 1546.
[24] Grenet C, Plinketi L, Veyret J B 1995 Ceramic Transactions 58 125
[25] Morscher G N Modeling the stress strain behavior of woven ceramic matrix composites 107th Annual American Ceramic Society Conference
[26] Murthy P L N, Nemeth N N, Brewer D N 2008. Composites B 39 694
[27] Zhu D M, Miller R A, Fox D S Thermal and environmental barrier coating development for advanced propulsion engine systems NASA/TM-2008-215040
[28] Bednarcyk B A, Mital S K, Pineda E J Multiscale modeling of ceramic matrix composites In Proceedings of 56th AIAA/ASCE/AHS/ASC Structures, Structural Dynamics, & Materials Conference. 5-9 January 2015, Kissimmee, Florida
[29] Nishio K, Igarashi K I, Take K 1999 ASME International Gas Turbine & Aeroengine Congress & Exhibition, 121 12
[30] Takashi T, Takeshi N 2005 IHI Engineering Review 38 58
[31] Li L B 2015 Applied Composite Materials 22 773
[32] Li L B 2015 Materials 8 8539