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FATIGUE CRACK INITIATION AND PROPAGATION FROM REINFORCEMENT FIBER ENDS FOR Ti-Alloy MATRIX COMPOSITES

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ABSTRACT

The partial reinforcement is very useful concept for a wide practical use of continuous fiber reinforced metal matrix composites (MMCs). It follows the reinforcement fiber ends in MMCs components as a necessary consequence. It is therefore very important to examine the influence of reinforcement fiber ends on long-term durability performance for ensuring structural integrity of MMCs components. This paper investigates the fatigue crack initiation and propagation behavior and summarizes the influence of continuous reinforcement fiber ends on low-cycle fatigue behavior for Ti-alloy matrix composite. The reinforcement fiber ends specimen has shorter fatigue lives than those of standard specimen. In particular, the surface fiber ends specimen has shorter fatigue lives as compared with those of inner fiber ends specimen. Cyclic stress-strain and stress-inelastic strain curve measurements indicate a significant difference in the response of these materials depending on the specimen type and strain level. These differences in the response suggest that fatigue crack initiation and propagation mechanisms play different roles in defining fatigue life.

KEYWORDS: Ti-alloy Matrix Composites, SP700, Low-cycle Fatigue, Reinforcement Fiber Ends, Fatigue Crack Initiation and Propagation, Fractographic Examinations, Prediction of Fatigue Lives

INTRODUCTION

Continuous fiber reinforced metal matrix composites (MMCs) have been researched and developed because of light-weight and high temperature capability for the past twenty years and characterized fatigue damage tolerance based on fracture mechanics [1~6]. They have been applied to various high temperature structural components in the field of aeronautics, aerospace and power generation industries. The continuous fiber partially reinforced Ti-alloy matrix composite rotor bladed ring has also been successfully fabricated on the basis of the design requirements [7,8]. It has been widely recognized that the partial reinforcement is very useful concept for a wide practical use. It followed the reinforcement fiber ends in MMCs components as a necessary consequence. It is therefore very important to investigate the influence of these fiber ends on long-term durability performance for ensuring structural integrity of MMCs components.

The final goal of this research is to establish not only the materials database but also the design database also included materials testing and evaluation and damage tolerance fatigue design concepts for continuous fiber reinforced Ti-alloy matrix composite (TMCs) rotating parts in aircraft engines, such as impellers, disks, integrally bladed rotors or bladed disks, and bladed rings now primarily fabricated of nickel based super-alloys. This paper investigates the fatigue crack initiation and propagation behavior and summarizes the influence of continuous reinforcement fiber ends on low-cycle fatigue behavior for Ti-alloy matrix composite.

MATERIALS AND EXPERIMENTAL PROCEDURE

Materials and Test Specimens

The materials investigated are unidirectional six- and seven-plies SCS-6/SP700 laminate composites. The composite panel was fabricated by hot isostatically pressing alternate layers of continuous SiC fibers, SCS-6 and thin Ti-alloy foils, SP700. Specimens used here are coupon-type with a dimension of 150 mm-long, 10 mm-width and 15 mm-gage length of 1.4~1.6 mm thickness as shown in Fig. 1. Taking account of the processing method of TMCs rotor bladed ring, two types of test specimen were prepared to examine the influence of reinforcement fiber ends on low cycle fatigue behavior. The simulated reinforcement fiber ends were introduced in the first ply layers light under specimen top surface (Type-I) and in the middle ply layer (Type-II) at the center of the gage section.

Experimental Procedure

The low-cycle fatigue tests lower than 10^5 cycles were performed at RT, 450 and 650℃ under strain-controlled mode at a frequency of 0.5 Hz with a constant strain ratio R_ε of 0.1 using a MTS 810 TestStar materials testing system. Measurements of cyclic stress-strain curves were conducted using extensometer with 10 mm gage length. Cycles to failure N_f was determined at a number of cycle of 25 % load-drop from the initial steady state. After the fatigue testing, fractographic examinations were performed on specimen surface and fracture surface in order to examine the low cycle fatigue crack initiation and propagation mechanism

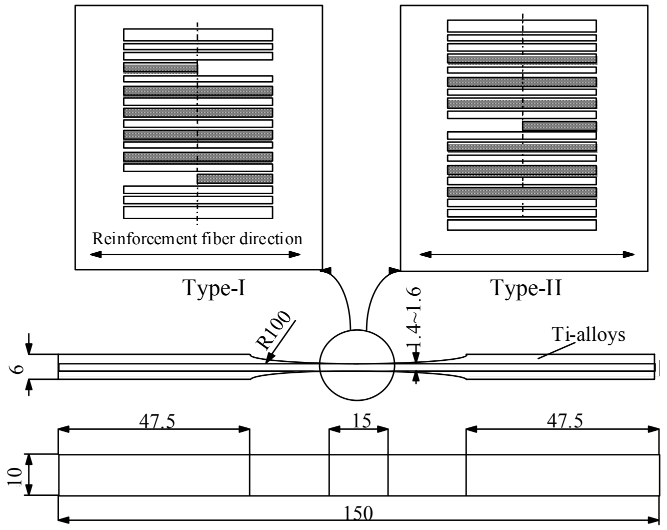

Figure 1: A schematic illustration of simulated reinforcement fiber ends and configuration and dimensions of fatigue test specimen.

EXPERIMENTAL RESULTS

Low-cycle Fatigue Lives

Relationships between total strain range $\Delta\varepsilon_t$ and cycles to failure N_f are shown in Fig. 2 for a comparison with standard specimen. These show the almost straight line in log-log plots and have same slope within the limits of this experiment, although there is a little scatter in fatigue lives at every type of specimen among the materials 11FY and 12FY. It can also be seen from this figure that the reinforcement fiber ends specimen has a shorter fatigue lives than those of standard specimen. It is fundamentally resulted from the difference in fatigue crack initiation and propagation behavior. Reinforcement fiber ends specimen has a shorter fatigue crack initiation lives as compared with standard specimen. And Type-I has a shorter fatigue lives than Type-II. It is concluded here that the reinforcement fiber ends near the surface is the most critical for the low cycle fatigue lives.

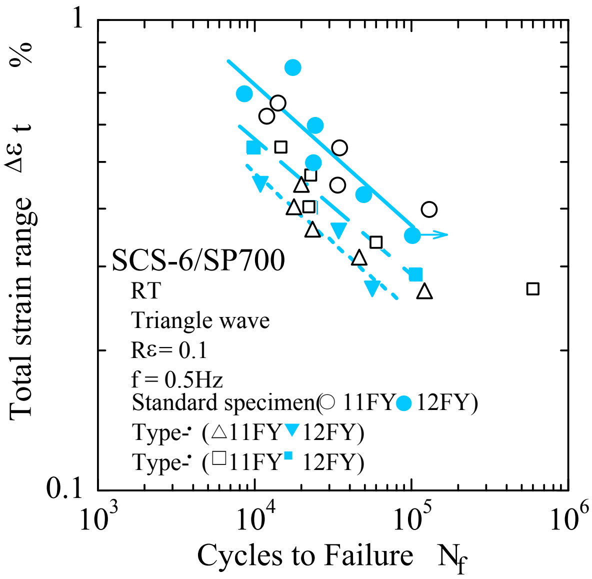

Figure 2: Relationships between total strain range $\Delta\varepsilon_t$ and cycles to failure N_f.

Also, Type-I, -II and standard specimen have different mechanical properties depending on fiber volume fraction and total number of laminates as cross section are shown in Fig. 1. Low-cycle fatigue lives curves normalized in terms of strain-to-failure ε_f are shown in Fig. 3. These curves have almost same slope. Reinforcement fiber ends specimen has smaller retention of strain-to-failure than those of standard specimen. In particular, there is a remarkable difference at high cycle region over 10^5 cycles. In a case of Type-I, the retention of strain-to-failure against the maximum low cycle fatigue strain determined at 10^5 cycles is the lowest, approximately 25 %. On the other hand, standard specimen kept at nearly 40 % level. Also, Type-I, that is, surface laminate layer reinforcement fiber ends specimen has smaller lives as compared with those of middle laminate layer reinforcement fiber ends specimen, Type-II. It should be noted here that TMCs have a lower design allowable in strain for low cycle fatigue, although they have also high strength characteristics.

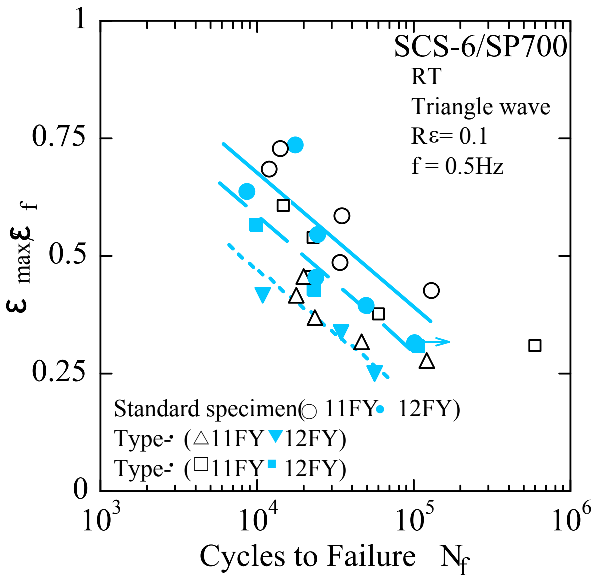

Figure 3: Normalized low cycle fatigue lives curves in terms of strain-to-failure ε_f.

Changes of Stress Amplitude during Fatigue Cycle

Changes of stress amplitude slightly depend on the maximum/minimum strain, strain amplitude and type of specimen. Generally, maximum stresses decreases with increasing of number of fatigue cycles, and then show the steady-state value. Finally, both maximum and minimum stresses decrease due to fatigue crack initiation and propagation, and then stress amplitude suddenly decreases near N_f cycles. Minimum stress is also reached to the negative value and the tension-compression fatigue behavior in the latter, although the strain ratio is controlled to the constant positive value. It is fundamentally resulted from the redistribution of residual stress in the matrix metal due to the fatigue crack initiation and propagation. Accordingly, there is a much difference between strain-controlled fatigue lives and stress-controlled fatigue lives.

Measurements of Cyclic Stress versus Strain Curves

Cyclic stress-strain and stress-inelastic strain curve measurements indicate a significant difference in the response of these materials depending on the strain level and type of specimen. There is also a quite influence of test temperature on low-cycles fatigue lives. These differences in the response suggest that fatigue crack initiation and propagation mechanisms play different roles in defining fatigue life. Generally, the slope of S-S curves gentle with increasing of fatigue cycles, and gradually show the hysteresis loop along with the increment of inelastic strain. There is also the distinct knee point in the S-S curve due to the fatigue crack closure behavior. Fatigue crack initiation life can be determined from this knee point of S-S curve. The ratio of fatigue crack initiation life to the total fatigue life is relatively small, and the low cycle fatigue lives for both Type-I and -II are fundamentally controlled by fatigue crack propagation life.

Fractographic Examinations

There is the tendency that some fatigue cracks initiated near the reinforcement fiber ends at both edge side where the fibers were exposed, and then joined to a main fatigue crack. It has already reported [9] there is no remarkable effect of the fiber exposure on the load-controlled fatigue lives for standard specimen. Some cases are that the main fatigue crack finally surrounded the whole specimen but the specimen was not failure due to the reinforcement fiber bridging even at N_f cycles.

SEM examinations of fatigue fracture surface are shown in Figs. 4(a), (b) and (c) for Type-I tested at ε_{max} of 0.3 %. It is terminated at N_f=1.2x10^5 cycles and then residual tensile test was performed to reveal fatigue fracture surface. There is a difference between fatigue fracture and monotonic failure regions in the matrix metal. Fractograph(a) show the dimple pattern fractured during the residual tensile test. Fractographs (b) and (c) indicate that not only the fatigue cracks initiated in the reinforcement fiber ends laminates layer but also many fatigue cracks radially propagated from the breakage fibers were observed in the middle laminate layers where there is no reinforcement fiber ends. There also observed some steps formed by joining some fatigue cracks in the middle laminate layers. It is concluded here that the fatigue cracks are not always initiated in the fiber ends laminate layer but in the middle laminate layers where it is very high stress (strain) states due to the reinforcement fiber ends as discussed in details in the later section.

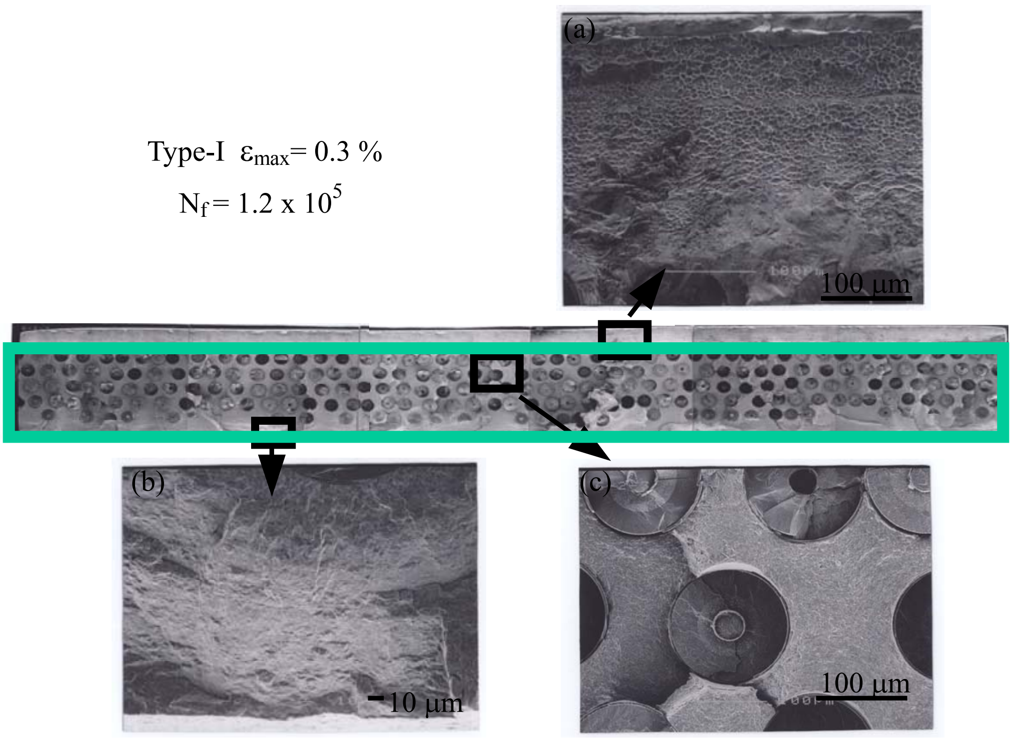

Figure 4: SEM examinations of fatigue fracture surface for Type-I tested at ε_{max}=0.3 %

DISCUSSION

Comparisons with Matrix Ti-alloys SP700

Comparisons of low cycle fatigue lives with matrix metals SP700 are shown in Fig. 5. There is little in-fluence of thermo-mechanical treatments on ultra-low cycle fatigue lives for SP700. It is shown from this figure that strain-controlled low cycle fatigue lives for TMCs are very small as compared with the extra-polation fatigue lives for SP700 shown by the solid line. It is presumed to be resulted from the residual tensile stress in the matrix metal induced during the fabrication process due to the mismatch of thermal expansion between the reinforcement fiber and matrix Ti-alloy.

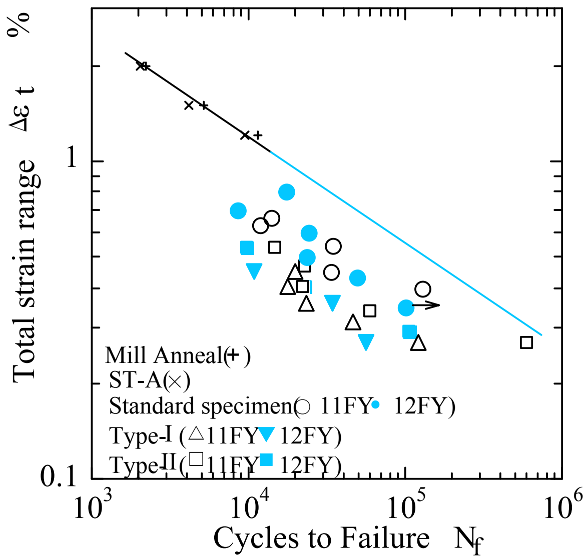

Figure 5: Comparisons of strain-controlled low cycle fatigue lives with matrix Ti-alloys SP700.

Analysis for Reinforcement Fiber Ends Specimen and Fatigue Lives Prediction

Fractographic examinations show that many fatigue cracks initiated and propagated even in the non-reinforcement fiber ends laminate layers. These are joined to the main fatigue crack. The fatigue crack propagation life mainly controlled low cycle fatigue life. There is fundamentally little difference in fatigue crack initiation and propagation mechanism between Type-I and -II specimens.

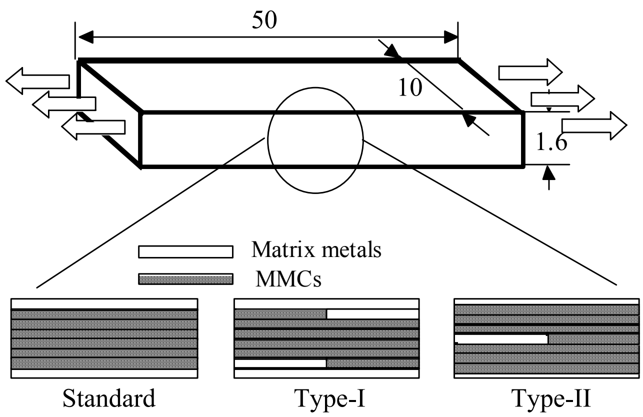

Figure 6: Schematics of analytical model

A macroscopic stress field of test specimen was analyzed based on a simple analytical model schematically shown in Fig. 6 [10]. These stress analyses show that the MMCs part of Type-I is highly stressed and quail-tatively corresponds to lower fatigue lives of Type-I. There is little difference in stress field of the MMCs part between standard specimen and Type-II. Accordingly, differences in low cycle fatigue lives between standard specimen and Type-II shown in Figs.2 and 3 cannot always rationalized by this macroscopic stress analysis. It is necessary for the future research to model fatigue crack initiation and propagation and consider the redistribution of residual stress for quantitative prediction of low cycle fatigue lives.

CONCLUSIONS

The influence of reinforcement fiber ends on low cycle fatigue behavior was investigated in order to establish the fatigue damage tolerance design concept for continuous fiber reinforced Ti-alloy matrix composite (TMCs) rotating parts in aircraft engines. The conclusions may be summarized as follows.

(1) Low cycle fatigue tests were successfully performed for the reinforcement fiber ends specimen simulated continuous fiber partially reinforced metal matrix composite components.

(2) There is a remarkable influence of reinforcement fiber ends on low cycle fatigue lives. The surface laminate layer reinforcement fiber ends specimen has the lowest fatigue lives. It is necessary for the fatigue damage tolerance design of continuous fiber partially reinforced metal matrix composites structural components to consider the influence of reinforcement fiber ends.

(3) Stress analyses of the reinforcement fiber ends specimen show that the lower fatigue lives of Type-I corresponds the highly stressed at the MMCs portion. It is also identical to the fractographic examinations that there are many fatigue cracks initiated and propagated in the laminate layers near the reinforcement fiber ends and joined by forming the steps to the main fatigue crack.

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