KINETIC MODEL FOR SELF-CRACK-HEALING IN CERAMICS AND POSSIBILITY OF TURBINE BLADE APPLICATIONS

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ABSTRACT

Self-crack-healing behaviors in alumina/ silicon carbide (SiC) nanocomposites (agent diameter of 270 nm) having the semi-eliptical surface crack were investigated at various healing temperatures T_H and oxygen partial pressures p_{O2} in standard pressure. The results showed the complete strength recovery was attained by heating at test temperature ranging between 1000^oC to 1550^oC in p_{O2} above active to passive transition p_{O2}^T. Furthermore, the minimum crack-healing time for complete strength recovery t_H^{Min} increased as decreasing p_{O2} within the p_{O2} ranging above p_{O2}^T. Based on the obtained results, the kinetics model for complete strength recovery by self-healing was proposed. Using the model, the t_H^{Min} in various p_{O2} for alumina/ SiC nanocomposites (argent diameter of 20 nm) were estimated. From the estimation, the possibilities of the self-crack-healing of two types of alumina/SiC composites in combustion gas atmosphere of aircraft engine and of turbine blade applications will be discussed.

1. INTRODUCTION

Self-crack-healing is one of the most valuable phenomena to overcome the reliability decrease of blittle ceramics that are caused by non-acceptable cracking in service. The reason is that the self-crack-healing atonomically attains complete recovery of damaged strength through the passive oxidation of SiC trrigered by cracking itself [1]. This feature allow the self-healing ceramics to be an attractive candidate for next-generation high temperature material which can be used as gas turbine components. i.e., turbine blade and vane in aircraft engine.

In this stady, we proposed the kinetics model for self-crack-healing in alumina/ SiC nanocomposites. Meanwhile, the combustion gas temperature and gas compositions within the ranging from high pressure turbibe HPT to low pressure turbine LPT blade and vane in aircraft engine, CF6 were calculated by Chemical Equilibrium with Applications developed by NASA [2]. From the findings, minimum healing time in combustion atomosphere of aircract engine were estimated.

2. EXPERIMENTAL AND ANALYSIS METHOD

Alumina/ 15 vol.% SiC nanocomposites (agent diameter of 270 nm) were used. The semi-eliptical surface crack with surface length of $100\mu m$ and aspect ratio of 0.9 was introduced by Vickers indentation method at the specimen. The cracked specimen
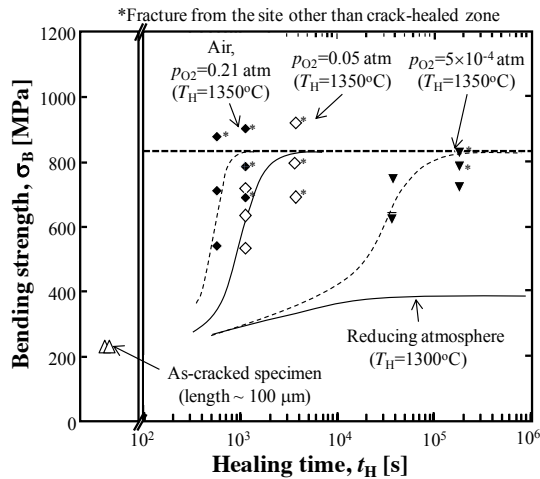
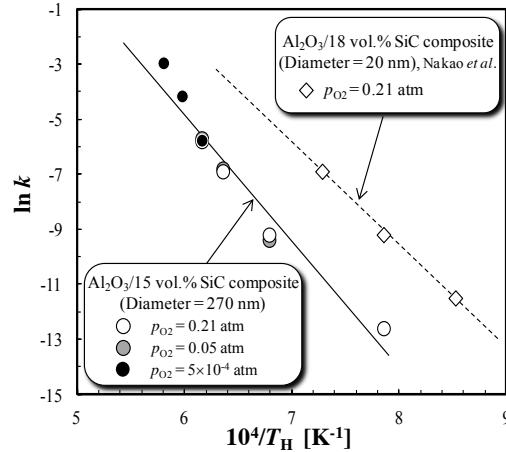Figure 1: Strength recovery behavior in amulina/SiC composite (270nm).

Figure 2: Arrhenius plot showing relationship between k and $1/T_H$.

were conducted to heating at the healing temperature of 1000°C - 1550°C for 6×10^2 - 1.8×10^5 s in various oxygen partial pressure, p_{O2}, of 5×10^{-4} atm and 0.05 atm controled by passing N_2/O_2 mixture gas through the furnace. Moreover, by passing the N_2 gas that was deoxidized by reacting with heated graphite, the specimen were subjected to reducing atmosphere. The strength recovery was investigated by the fracture test performed on three-point loading system with a span of 16 mm.

Temperature, pressure and gas compositions at blade and vane from 1st stage HPT to last stage LPT were estimated on the basis of chemical thermodynamics. For analysis, CF6 engine having 2 stage HPT and 5 stage LPT as illustrated in figure 3 was used. Temperature and gas compositions after combusion of the mixture gas of compressed air and fuel (JET-A1, $C_{12}H_{23}$) were estimated using NASA-CEA program [2], considering the chemical equiliburume of various gas spicies. In the calculation, the air-fuel ratios A/F were veried from 4 to 80. The used Mach number was 0.8. All the turbine blade and vane were not cooled by compressed air.

3. RESULTS AND DISCUSSION

3.1 KINETICS FOR SELF-CRACK-HEALING

Figure 1 shows the strength recovery behaviors of alumina/15 vol% SiC composite (270nm) at 1350°C in various p_{O2} above the active to passive transition p_{O2}^T reported by Hinze and Graham [3]. The behaviors at 1300°C in reducing atmosphere corresponding to the active oxidation condition are also shown in the figure. The complete strength recoveries can be attained only by the passive oxidation:

$$SiC(s) + \frac{3}{2}O_2(g) = SiO_2(s) + CO(g) \tag{1}$$

Meanwhile, The crack-healing was not attained by active oxidation: $SiC(s) + O_2(g) = SiO(g) + CO(s)$, below the p_{O2}^T. Meanwhile, the minimum healing time for the complete strength recovery t_H^{min} increased with decreasing p_{O2}. Thus, the strength recovery rate v_H (=$1/t_H^{Min}$) can be given by

$$v_H = \frac{1}{t_H^{Min}} = k\left(a_{SiC}\, a_{O_2}^{3/2}\right)^n \tag{2}$$

where a_{SiC} and a_{O2} are the activity of SiC and O_2, respectively. Since SiC is a solid phase, $a_{SiC} = 1$. a_{O2} can be expressed by ration of p_{O2} to standerd pressure P^o (=1

atm). n is a temperatrue indipendent constant and has reported to be 0.557 [1]. Meanwhile, the k is the rate constant for strength recovery as given by :

$$k = A_{\text{H}} \cdot \exp\left(\frac{-Q_{\text{H}}}{RT_{\text{H}}}\right) \tag{3}$$

where A_{H}, Q_{H}, R are the frequency factor, activation enegy for self-crack-healing and gas constant. Thus, kinetic equation for strength recovery can be given by

$$v_{\text{H}} = k\left(\frac{p_{\text{O2}}}{P^\circ}\right)^{3n/2} = A_{\text{H}} \cdot \exp\left(\frac{-Q_{\text{H}}}{RT_{\text{H}}}\right)\left(\frac{p_{\text{O2}}}{P^\circ}\right)^{3n/2} \tag{4}$$

Figure 2 shows the Arrhenius plot showing relationship between k and $1/T_{\text{H}}$. The data for nanocomposite (20 nm) [4] togather with nanocomposite (270 nm) were shown in the figiure, assuming that the n in both nanocomposites are same value. As shown in the figure, ln$k$ showed in good agreement with Arrhenius' law. From the intercept and slope of the streight line fitting the data plots, the values of A_{H} and Q_{H} can be determined to be 1.04×10^{10} s^{-1} and 387 kJ/mol, respectively, for alumina/SiC nanocomposites (270 nm) and to be 4.87×10^{8} s^{-1} and 308 kJ/mol, respectively, for alumina/SiC nanocomposites (20 nm). The obtained A_{H} for the healing by the argent with a diameter 20 nm exhibited about 21 times larger than that with a diameter of 270 nm. This is mainly due to the fact that the specific surface area of SiC increases with decreasing agend diameter, leading to the rapid oxidation of SiC.

3.2 COMBUSTION GAS PROPERTIES

Figure 3 (a) shows the gas temperatrue and pressure at the compressor and turbine part. Temperature T_i and pressure P_i at i th stage compresor vane or blade in CF6 engine were calculated based on adiabatic compresson and stagnation as follows:

$$T_i = T_o\left(\frac{A_o}{A_i}\right)^{\gamma-1}\left\{1 + \left(\frac{\gamma-1}{2}\right)M^2\right\}, \quad P_i = P_o\left(\frac{A_o}{A_i}\right)^{\gamma}\left\{1 + \left(\frac{\gamma-1}{2}\right)M^2\right\}^{\gamma/(\gamma-1)} \tag{5 and 6,}$$

respectively, where T_o and P_o are inlet temperature and pressure, and correspond to 273.15 K and 1 atm, respectively. γ is the ration of specific heat at constant pressure C_p and volume C_v of chemically equiliburume air, and almost equal 1.38. A_o and A_i are throat area of compressor inlet and i th stage compressor vane or blade, respectively. Thus, the gas temperature and pressure of compressed air can be calclated to be 755.8 K and 27.1 atm at last stage of compressor, respectively.
From the ontained compressed air properties and A/F values, T_1 at the 1st stage vane in turbine part after combustion, coresponding to TIT, can be calculated using

NASA-CEA program. Wen A/F =39.7, TIT was estimated to be 1500°C. The T_i and P_i in turbine part were also shown in figure 4 (a). As shown in the figure, gas temperatrue and pressure in the turbine part decreased with increasing the distance from fan blade by adiabatic expansiton.
Figure 3 (b) shows the gas compositions at compressor and turbine parts calculated from several T_i and P_i, when A/F = 39.7. As shown in the figure, x_{O2} were calculated to be approximately 0.108 at all points in the turbine part. The value showed significuntly higher than the active to passive transition $p_{\text{O2}}{}^{\text{T}}$ discussed above.
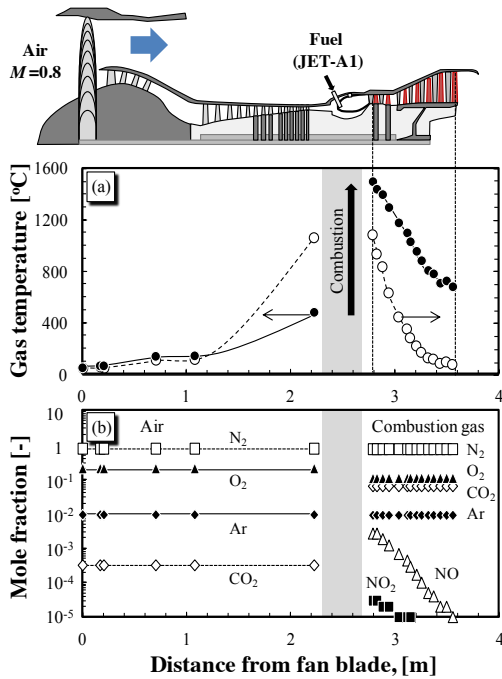
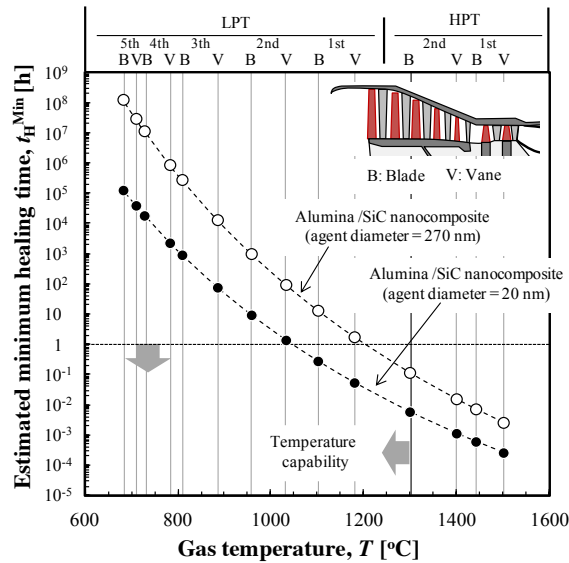Figure 3: Temperatrue, pressure and compositions estimated in CF6 engine.

Figure 4: Minimum healing time esmtimated at turbine blades and vanes.

3.3 POSSIBILITY OF TURBINE BLADE APPLICATIONS

It can be expected that the minimum healing time varys depending on T_i, P_i and x_{O2}. Assuming that the combustion gas is the ideal gas, the p_{O2} can be given by

$$p_{O2} = x_{O2}P_i \tag{7}$$

Thus, strength recovery rate by self-healing of semi-eliptical surface crack with a length of 100 μm initiated at the i th tubine vane and blade of the amulina/SiC composites can be estimated as follows:

$$v_H = \frac{1}{t_H^{min}} = A_H \cdot \exp\left(\frac{-Q_H}{RT_i}\right)\left(\frac{x_{O2}P_i}{P^\circ}\right)^{3n/2} \tag{8}$$

Figure 4 shows the minimum healing time esmtimated from 1st stage HPT vane to 5th stage LPT blade for two types of nanocomposites. As shown in figure, t_H^{Min} decrease with increasing gas temperatrue and pressure. On the other hand, the temperatrue capability of the alumina/SiC nanocomposite has reported to be apploximatry 1300°C [4]. Assuming that it is requried to completely heal the crack within 1 hour for self-healing in service, it can be confirmed that self-healing can be attained at 2nd stage HPT blade for nanocomposite (270nm), and at 2nd stage HPT blade, 1st stage LPT vane and blade for nanocomposite (20 nm), respectively.

4. CONCLUSIONS

Kinetic study for self-crack-healing and estimation of combustion gas properties indicated that self-crack-healing ceramics can be expected to be used as turbine blade and vane. The finding obtained here will also make a large contribution to the design gas turbine materials with self-healing.

ACKNOWLEDGEMENTS

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