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-elliptical surface crack were investigated at various healing temperatures $T_H$ and oxygen partial pressures $p_{O_2}$ in standard pressure. The results showed the complete strength recovery was attained by heating at test temperature ranging between 1000°C to 1550°C in $p_{O_2}$ above active to passive transition $p_{O_2}^T$. Furthermore, the minimum crack-healing time for complete strength recovery $t_{H_{Min}}$ increased as decreasing $p_{O_2}$ within the $p_{O_2}$ ranging above $p_{O_2}^T$. 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 $p_{O_2}$ for alumina/SiC nanocomposites (agent 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 brittle 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 triggered 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 study, 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 turbine 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-elliptical surface crack with surface length of 100μm and aspect ratio of 0.9 was introduced by Vickers indentation method at the specimen. The cracked specimen
were conducted to heating at the heating temperature of 1000°C - 1550°C for \( 6 \times 10^2 \) - \( 1.8 \times 10^5 \) s in various oxygen partial pressure, \( p_{O_2} \), of \( 5 \times 10^{-4} \) atm and 0.05 atm controlled 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 combustion 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 equilibrium of various gas species. In the calculation, the air-fuel ratios \( A/F \) were varied 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 \( p_{O_2} \) above the active to passive transition \( p_{O_2}^T \) 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:

\[
SiC(s) + \frac{3}{2} O_2(g) = SiO_2(s) + CO(g)
\]

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

\[
v_H = \frac{1}{t_{H}^{\text{min}}} = k \left( a_{SiC} a_{O_2}^{3/2} \right)^n
\]

where \( a_{SiC} \) and \( a_{O_2} \) are the activity of SiC and \( O_2 \), respectively. Since SiC is a solid phase, \( a_{SiC} = 1. \) \( a_{O_2} \) can be expressed by ration of \( p_{O_2} \) to standard pressure \( P^0 \) (=1

\[
\begin{align*}
\text{Healing time, } t_H \text{ [s]} & \quad \text{Bending strength, } \sigma_B \text{ [MPa]} \\
\text{Air, } p_{O_2}=0.21 \text{ atm } \left( T_H=1350^oC \right) & \quad 1200 \quad 600 \quad 400 \quad 200 \quad 0 \\
\text{Air, } p_{O_2}=0.05 \text{ atm } \left( T_H=1350^oC \right) & \quad 1200 \quad 600 \quad 400 \quad 200 \quad 0 \\
\text{Air, } p_{O_2}=5 \times 10^{-4} \text{ atm } \left( T_H=1350^oC \right) & \quad 1200 \quad 600 \quad 400 \quad 200 \quad 0 \\
\text{Reducing atmosphere } \left( T_H=1300^oC \right) & \quad 1200 \quad 600 \quad 400 \quad 200 \quad 0 \\
\end{align*}
\]

Figure 1: Strength recovery behavior in alumina/SiC composite (270nm).
\( n \) is a temperature independent constant and has reported to be 0.557 [1]. Meanwhile, the \( k \) is the rate constant for strength recovery as given by:

\[
k = A_H \cdot \exp \left( \frac{-Q_H}{RT_H} \right)
\]

where \( A_H, Q_H, R \) are the frequency factor, activation energy for self-crack-healing and gas constant. Thus, kinetic equation for strength recovery can be given by

\[
v_H = k \left( \frac{P_{O_2}}{P} \right)^{3n/2} = A_H \cdot \exp \left( \frac{-Q_H}{RT_H} \right) \left( \frac{P_{O_2}}{P} \right)^{3n/2}
\]

Figure 2 shows the Arrhenius plot showing relationship between \( k \) and \( 1/T_H \). The data for nanocomposite (20 nm) [4] together with nanocomposite (270 nm) were shown in the figure, 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 straight line fitting the data plots, the values of \( A_H \) and \( Q_H \) can be determined to be \( 1.04 \times 10^{10} \text{ s}^{-1} \) and \( 387 \text{ kJ/mol} \), respectively, for alumina/SiC nanocomposites (270 nm) and to be \( 4.87 \times 10^{10} \text{ s}^{-1} \) and \( 308 \text{ kJ/mol} \), 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 temperature and pressure at the compressor and turbine part. Temperature \( T_i \) and pressure \( P_i \) at \( i \)th stage compressor vane or blade in CF6 engine were calculated based on adiabatic compression and stagnation as follows:

\[
T_i = T_0 \left( \frac{A_0}{A_i} \right)^{Y^{-1}} \left\{ 1 + \left( \frac{y-1}{2} \right) M^2 \right\}, \quad P_i = P_0 \left( \frac{A_0}{A_i} \right)^{Y} \left\{ 1 + \left( \frac{y-1}{2} \right) M^2 \right\}^{Y/(Y-1)}
\]

where \( T_0 \) and \( P_0 \) are inlet temperature and pressure, and correspond to 273.15 K and 1 atm, respectively. \( Y \) is the ratio of specific heat at constant pressure \( C_p \) and volume \( C_v \) of chemically equiliburume air, and almost equal 1.38. \( A_0 \) 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 calculated to be 755.8 K and 27.1 atm at last stage of compressor, respectively.

From the obtained compressed air properties and A/F values, \( T_1 \) at the 1st stage vane in turbine part after combustion, corresponding 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 temperature and pressure in the turbine part decreased with increasing the distance from fan blade by adiabatic expansion.

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, \( x_{O_2} \) were calculated to be approximately 0.108 at all points in the turbine part. The value showed significantly higher than the active to passive transition \( p_{O_2} \) discussed above.
3.3 POSSIBILITY OF TURBINE BLADE APPLICATIONS

It can be expected that the minimum healing time varies 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

$$ p_{O2} = x_{O2} P_i $$

(7)

Thus, strength recovery rate by self-healing of semi-elliptical surface crack with a length of 100 $\mu$m initiated at the $i$th stage turbine vane and blade of the alumina/SiC composites can be estimated as follows:

$$ v_H = \frac{1}{t_{H min}} = A_H \cdot \exp \left( \frac{-Q}{RT_i} \right) \left( \frac{x_{O2} P_i}{P^*} \right)^{3n/2} $$

(8)

Figure 4 shows the minimum healing time estimated 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 temperature and pressure. On the other hand, the temperature capability of the alumina/SiC nanocomposite has reported to be approximay 1300°C [4]. Assuming that it is required 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.
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