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# Development of strength evaluation method for high-pressure ceramic components

Hiroaki Takegami*, Atsuhiko Terada, Yoshiyuki Inagaki

*Japan Atomic Energy Agency, 4002 Narita-cho, Oarai-machi, Ibaraki-ken 311-1393, Japan*

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ABSTRACT

Japan Atomic Energy Agency is conducting R&D on nuclear hydrogen production by the Iodine-Sulfur (IS) process. Since highly corrosive materials such as sulfuric and hydriodic acids are used in the IS process, it is very important to develop components made of corrosion resistant materials. Therefore, we have been developing a sulfuric acid decomposer made of a ceramic material, that is, silicon carbide (SiC), which shows excellent corrosion resistance to sulfuric acid. One of the key technological challenges for the practical use of a ceramic sulfuric acid decomposer made of SiC is to be licensed in accordance with the High Pressure Gas Safety Act for high-pressure operations of the IS process. Since the strength of a ceramic material depends on its geometric form, etc., the strength evaluation method required for a pressure design is not established. Therefore, we propose a novel strength evaluation method for SiC structures based on the effective volume theory in order to extend the range of application of the effective volume. We also developed a design method for ceramic apparatus with the strength evaluation method in order to obtain a license in accordance with the High Pressure Gas Safety Act. In this paper, the minimum strength of SiC components was calculated by Monte Carlo simulation, and the minimum strength evaluation method of SiC components was developed by using the results of simulation. The method was confirmed by fracture test of tube model and reference data.



## 1. Introduction

Japan Atomic Energy Agency (JAEA) is conducting R&D on nuclear hydrogen production by the Iodine-Sulfur (IS) process (Onuki et al., 1994; Kasahara et al., 2007). Since highly corrosive materials such as sulfuric and hydriodic acids are used in the IS process, it is very important to develop components made of corrosion resistant materials. Therefore, we have been developing a sulfuric acid decomposer made of a ceramic material, that is, silicon carbide (SiC) (Terada et al., 2006), which shows excellent corrosion resistance to sulfuric acid (Kubo et al., 2003).

In Japan, one of the key technological challenges for the practical use of a ceramic sulfuric acid decomposer made of SiC is to be licensed in accordance with the High Pressure Gas Safety Act for high-pressure operations of the IS process. In order to obtain the license, strength evaluation method for ceramic components is required. Since the strength of a ceramic material depends on its geometric form, etc., the strength evaluation method required for a pressure design is not established.

Therefore, we proposed a strength evaluation method for SiC components based on the effective volume theory (Takegami et al., 2011). It is difficult, however, to improve the accuracy of the proposed method due to large cost and time for a number of fracture tests of SiC components.

In this paper, an analytic approach was applied for developing a strength evaluation method. The minimum strength of SiC components was calculated by Monte Carlo simulation, which can calculate many times easily with a personal computer. By using the simulation results, we developed a strength evaluation method for SiC components.

## 2. Experimental procedure

### 2.1. Calculation model

A pressureless sintered SiC, which was formed by cold isostatic pressing (CIP), was selected for the strength evaluation of this study.

A calculation model of a SiC component was prepared for strength evaluation by Monte Carlo simulation. In order to focus on the relation between strength and flaw size, uniaxial tensile stress was applied to the calculation model in this simulation. Assuming the relation between fracture stress and flaw size according to the

* Corresponding author. Tel.: +81 29 266 7667.
*E-mail address:* takegami.hiroaki@jaea.go.jp (H. Takegami).

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principles of fracture mechanics, the strength of a SiC component is determined by the maximum flaw size in the component under uniaxial tensile stress.

At the first step, distribution characteristics of flaw in a SiC component were determined. When SiC component strength fits to two-parameter Weibull distribution functions and fracture stress of a flaw can be described by fracture criteria $K = K_{IC}$, where $K$ is the stress intensity factor and $K_{IC}$ is the fracture toughness, the distribution of flaw diameter $d$ in the component $F_0(d)$ was given by the following relation obtained by Ichikawa (Ichikawa, 1985):

$$F_0(d) = 1 - \left(\frac{d_0}{d}\right)^{\kappa} \tag{1}$$

where $d_0$ is the parameter relation to length and $\kappa$ is the index of scatter.

The total number of flaws in the component $N$ is also given by

$$N = \delta V, \tag{2}$$

where $\delta$ is the number of flaws per unit volume and $V$ is the volume of the component.

At the second step, the component strength corresponding to the flaw characteristics was determined as follows. When the penny-shaped flaw in the cross section of component is applied tensile stress, $K$ is defined as:

$$K = M_T\left(\frac{2}{\pi}\right)\sigma\sqrt{\pi a}, \tag{3}$$

where $a$ is the flaw half-length, $M_T$ is correction factor for $K$. The value of $M_T$ is varied from 1.001 to 1.359 depending on the flaw position.

By using the equivalent flaw length $a_{eq}$, Eq. (3) is also described as:

$$K = \sigma\sqrt{\pi a_{eq}} \tag{4}$$

thus,

$$a_{eq} = a\left(\frac{2M_T}{\pi}\right)^2. \tag{5}$$

Hence, fracture stress $\sigma$ with respect to the small flaw in a component is given by:

$$\sigma = \frac{K'_{IC}}{\sqrt{a_{eq} + a_{eq0}}}, \tag{6}$$

where $K'_{IC}$ is the constant related to the fracture toughness and $a_{eq0}$ is the correction term of flaw length.

### 2.2. Strength test by Monte Carlo simulation

The calculation model consists of distribution characteristic of flaw and component strength as mentioned above. The value of parameters in each equation was determined for strength evaluation as follows.

Based on the relationship between fracture stress and equivalent flaw length in SiC (Machida et al., 1994) plotted by solid circles in Fig. 1, $K'_{IC}$ and $a_{eq0}$ in Eq. (6) were determined as 2200 MPa $\cdot \sqrt{\mu m}$ and 13 $\mu$m, respectively. The solid curve in Fig. 1 was obtained by substituting these values into Eq. (6).

$\delta$, $d_0$ and $\kappa$ in Eqs. (1) and (2) were 5, 14 and 4, respectively, which were determined by fitting the simulated 3-point bending test data by Monte Carlo method based on the procedure by Taniguchi et al. (Taniguchi et al., 1989), using the value of $K_{IC}$' and $a_{eq0}$, to experimental data.

Although $M_T$ is a variable related to the position of flaw, it was reported that the scatter of strength in lower strength region was better fitted to the distribution curve obtained by maximum value of $M_T$, 1.359 (Taniguchi et al., 1989). Therefore, $M_T$ was fixed to 1.359 regardless a flaw position in this study.

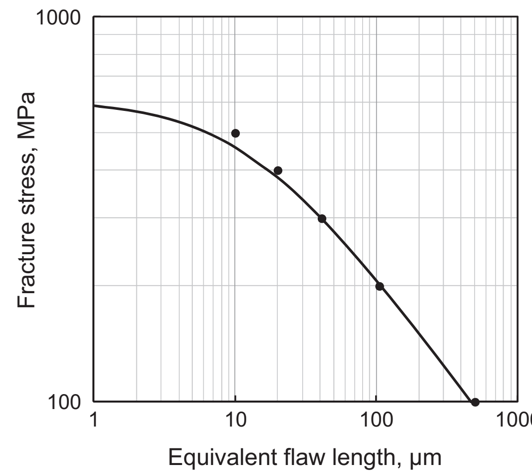


**Fig. 1.** Relationship between fracture stress and equivalent flaw length in SiC.

The volumes of SiC components calculated in this study were listed in Table 1. In each volume, flaw distribution was determined by inverse function method with Eqs. (1) and (2). After calculation of fracture stress of all flaws in the component by Monte Carlo simulation, tensile strength of the volume was determined as the lowest fracture stress of all flaws. This calculation was operated 300 times in each volume, and maximum strength, minimum strength, average strength and the Weibull modulus were calculated.

## 3. Results and discussion

### 3.1. Results of Monte Carlo simulation

Fig. 2 shows the strength distribution of SiC component calculated by Monte Carlo simulation. The maximum strength, the minimum strength, the average strength and the Weibull modulus of each volume are listed in Table 1. The strength and Weibull modulus were varied depending on the component volume.

Fig. 3 shows the strength fluctuation and the Weibull modulus in each volume. The maximum, minimum and average strength were decreased with increasing volume. Although the Weibull modulus also decreased with increasing volume, it became constant over 2000 mm$^3$.

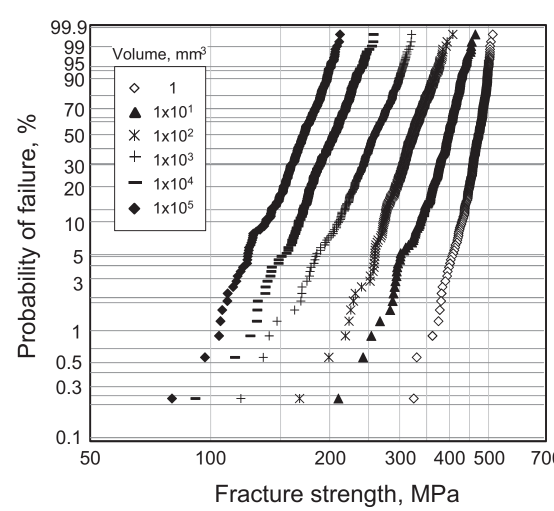


**Fig. 2.** Strength distribution of SiC component calculated by Monte Carlo simulation.