A Phenomenological Model for Cyclic Plastic Deformation

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ABSTRACT

A new concept directly founded on the basic material characteristics is proposed to represent the cyclic stress-strain relationship of the cyclic hardening materials. The present phenomenological model which is formulated in accordance with this concept can reasonably express the cyclic stress-strain behavior of the structural materials. And by incorporation of a fatigue damage accumulation factor into this method as the parameter of cyclic strain hardening, the cyclic stress-strain behavior at any cycles can be predicted adequately.

The present method is applied to describe the cyclic stress-strain hysteresis loop of JIS SUS304 which is one of the main structural materials for FBR components. The predicted behavior show good agreements with its experimental results.

1 INTRODUCTION

It is important that the inelastic behavior of the structural materials at elevated temperatures can be evaluated accurately with considering the inherent scattering of them for the design of Fast breeder reactor (FBR) components. Authors already presented a simple model for the inelastic structural analysis (Wada et al., 1986) from the point of view of the actual application. However, the more accurate constitutive equation is required for the rational, economic and safe design of large scaled FBR components. Many investigation on the constitutive equation are conducted by so many researchers (Inoue et al., 1989). Most of those models have some problems for the actual applications. Some models must require a lot of parameter/material constant to express the inelastic behavior of the materials accurately. Some models can be applied only to a certain load condition.

A new concept is proposed to represent the cyclic stress-strain behavior of the structural materials at elevated temperatures. In this concept, the behavior of a material can be essentially expressed by using only its true stress-strain relationship (the monotonic stress-strain relationship) and its cyclic stress-strain hysteresis loop at the steady state (about mid-life of continuous low cycle fatigue test).

The present approach is applied to the description of the cyclic stress-strain hysteresis curves of JIS SUS304 which is one of the main structural materials for Japanese FBR components. The continuous cyclic stress-strain SMiRT 11 Transactions Vol. 1 (August 1991) Tokyo, Japan, © 1991
behavior under the constant strain controlled condition and the strain change condition are predicted by the present model. The prediction of the variation of stress range under a cyclic load condition is compared with several experimental data and the analytical result by a finite element method code into which the other constitutive equation for cyclic plasticity is incorporated.

2 REPRESENTATION OF CYCLIC STRESS-STRAIN BEHAVIOR

2.1 BASIC MATERIAL DATA

This concept is only founded on the basic material characteristic data derived from the ordinary basic material test such as tensile and low cycle fatigue (LCF) test. In this concept, any special material tests are not necessary to decide the parameters in the constitutive equation for cyclic plasticity. In this method, only three material properties and one material constant are necessary for the representation of the cyclic stress-strain relationship of a material. The three material properties are the monotonic stress-strain relationship, the cyclic stress-strain relationship and the cyclic stress-strain hysteresis loop at steady state. A material constant indicates the tendency of cyclic hardening, which is described in detail in later section. The monotonic stress-strain relationship is observed in the ordinary tensile tests. Both the cyclic stress-strain behavior and the material constant are obtained from the continuous cyclic fatigue tests.

2.2 CONCEPT OF THE REPRESENTATION METHOD

The cyclic stress-strain relationship of the cyclic hardening materials under elevated temperatures is estimated from the initial state to the steady state (about mid-life of the LCF life) by the present concept as follows.

Assumption
(a) Two physical region are defined in the cyclic stress-strain behavior of a material. One is the contribution part to the cyclic hardening/softening process (CP process) and the other is the part of the simple unloading/loading process (SP process).
(b) An effective stress is defined as the difference between actual stress and the stress at the proportional limit.
(c) The linearity of the correlation between the effective stress and the plastic strain on the logarithmic graph.

Analytical step
(1) The stress-strain behavior is expressed by the monotonic stress-strain relationship during the initial state till the first unloading point (See Fig.1(1):CP process-1).
(2) The simple unloading behavior in the secondary stage where is the region from the peak stress in tensile side (the first unloading point) to an equivalent stress level to the first unloading point in compression side, is estimated by the steady state hysteresis loop (See Fig.1(2):SP-1). This estimated behavior must be corrected by considering the difference of stress range at the steady state from that at first cycle. The material parameters in the basic material characteristic equations are revised based on the parameter for the cyclic strain hardening (See Fig.1(3)). This parameter is reported in the next section.
(3) In the third stage where is the region from the equivalent stress level in
compression side to the peak stress in compression side (the secondary unloading point), the material behavior is expressed by the monotonic stress-strain relationship as the first stage (See Fig.1(4): CP-2).

(4) The following material behavior is represented by using its monotonic stress-strain relationship in CP stage and by using the steady state stress-strain hysteresis loop in SP stage periodically.

2.3 STRAIN HARDENING PARAMETER

A parameter which can indicate the proper strain hardening ratio under any loading conditions is decided based on the LCF test data. In general, the variation of stress range under the continuous strain controlled cyclic loading is strongly dependent on all test condition such as strain range, strain rate and test temperature. Figure 2 shows that the variations of stress range in so many ordinary LCF tests are rearranged by the accumulation of fatigue damage. The strain hardening ratio per a cycle is expressed the normalized stress by the stress at steady state in this figure. Those test data are 76 data points derived from the LCF test under several test conditions. This figure indicates that the strain hardening ratio (the hardening parameter) can be expressed by a relational equation as a function of fatigue damage fraction without any other elements such as strain range and temperature. The cyclic strain hardening ratio is expressed as follows (See Fig.3).

\[
\begin{align*}
\log(R) &= A + B \log(z) \quad (1) \\
R &= 1.0 \quad (2)
\end{align*}
\]

where \( R \) is the cyclic strain hardening ratio (the ration of the actual stress to the stress at steady state), \( a \) is the material constant which indicates the saturation point of the cyclic strain hardening. Factor \( A \) and \( B \) in Eq.(2) can be decided by material parameter \( w \) and \( x \) and the fatigue damage. \( w \) and \( x \) are calculated by using the monotonic stress-strain relationship and the cyclic one.

3 APPLICATION AND DISCUSSION

The present approach is applied to the description of the cyclic stress-strain behavior of JIS SUS304 which is one of the main structural materials in Japanese FBR components. The monotonic stress-strain relationship, the cyclic stress-strain relationship and the steady state stress-strain hysteresis loop of the material were given in reference(1). It is noted that those basic properties are described by the same Ludwik type equations respectively. The process of formulation of these properties and some material constants in each equations were reported in the previous paper (Wada et al., 1986). That is a typical cyclic hardening material and the parameter "a" is 0.02 which is derived from Fig.2.

The continuous cyclic stress-strain hysteresis loop under the constant strain controlled condition and the strain change condition are expressed by the present method. The examples of analytical results by the present method are shown in Fig. 4. Figure 4(a) is the predicted result for the observed one under the strain-controlled continuous cyclic loading at 450°C and at strain range of 0.7% and Fig. 4(b) also shows the predicted result for the other experimental data at 550°C at strain range of 1.0%. The broken lines and the solid lines are the observed data and the predicted results in both figures.
respectively. A little difference is found out between both predicted curves and observed ones in each figure. This fact suggests some limitations from the applied basic material properties. For example, the assumption that its proportional limit keeps a constant value both in its monotonic stress-strain relationship and in its cyclic stress-strain relationship under the same temperature, must be still more discussed. And the predictability of Ludwik type equation must be also considered especially at lower strain range. These results indicate that the present method can represent the cyclic stress-strain hysteresis loop of SUS304 adequately.

Figure 5 shows the variations of stress range under the strain-controlled continuous cyclic loading. The predicted result (solid line) indicates good agreement with the observed lines (some thin broken lines). The thick broken line is the analytical result by FEM with the Ohno’s model (Ohno et al. 1986) which adopts a two-surface theory and non-hardening region. The comparison between the predicted result by the present method and the analytical result by FEM indicates the effectiveness of application of this method to the actual structural analysis.

4 CONCLUSIVE REMARKS

(1) A new representation method directly based on some material test data is proposed for the cyclic stress-strain behavior of SUS304 which is a main structural material for Japanese PFR components.

(2) The present method indicates that a cyclic stress-strain hysteresis loop of the material at any number of cycles can be represented by its monotonic stress-strain relationship and its stress-strain hysteresis loop at steady state (about half of a LCF life).

(3) By introduction of LCF damage factor into the representation method, cyclic stress-strain relationship through a LCF life including the initial state of the material test can be expressed at any temperatures and at any strain ranges.

(4) The present method can give good predictions for the cyclic stress-strain behavior of SUS304 as compared with experimental data.

(5) The predicted curves of the variation of stress under the constant strain cyclic load condition show good agreements with the observed material behavior and the analytical results of a finite element method code into which the other constitutive equation for cyclic plasticity is incorporated.

REFERENCES


1. $0 \leq \varepsilon \leq \varepsilon_{\text{max. 1}}$

2. $\sigma_{\text{max. 1}} \leq \sigma \leq \sigma_{\text{max. 1}}$

Steady State Cyclic Stress Strain Hysteresis Loop

3. Correction of Material Parameters

4. $\varepsilon \leq \varepsilon_{\text{max. 2}}$

$F' = (K', m')$

$F = (K, m)$

$2 \sigma_d - 2 \sigma_v$

$2 \sigma_d - 2 \sigma_v$

Monotonic Stress Strain Relationship

Fig. 1. Concept of Phenomenological Representation Model

Material: SUS304
Strain Rate: 0.1%/sec

Fig. 2. Relationship between Fatigue Damage and Strain Hardening
Fig. 3. Concept of Strain Hardening Parameter as a Function of Fatigue Damage

Fig. 4. Examples of Representation of Cyclic Stress-Strain Hysteresis Loop

Fig. 5. Variation of Stress Range under Cyclic Loading