Nondestructive Evaluation of Creep Damage Using Leaky Surface Acoustic Wave Technique*

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Creep has been one of the most concerned matters on high temperature components of thermal power plants, petrochemical plants, oil refineries and so on. In present study, leaky surface acoustic wave (LSAW) has been applied to detect and evaluate the creep. LSAW signals with broad-band frequency generated by large-aperture-angle line-focus transducer were analyzed. The feature parameters of LSAW pulse both in time domain and in frequency domain such as amplitude of signal and ultrasonic power spectrum vary with creep process. Particularly high frequency components of LSAW attenuate through the mechanism of sound wave scattering by creep voids and cavities. Consequently ultrasonic spectroscopy technique can be expected to be available for deducing the state of deterioration in material quantitatively on the basis of correlation between microstructure in long-term operation at high temperature and ultrasonic propagation characteristics theoretically and practically.

Key Words: Creep, Nondestructive Evaluation (NDE), Ultrasonic, Leaky Surface Acoustic Wave (LSAW), Welds, Heat Affected Zone (HAZ)

1. Introduction

An assessment of remaining life of high temperature components expected to creep damage in thermal power plants, petrochemical plants and oil refineries have commonly been investigated by metallographic observation on material microstructure using replication testing. However, this method likely exhausts so much time for surface preparation by polishing, etching and printing, and the inspection area should be limited to only small fraction of the components. Therefore, an alternative in-situ method in field inspection has been strongly required.

Ultrasonic method is regarded as one of the effectual methods for assessing the material degradation. Above all leaky surface acoustic wave (LSAW) that is commonly used for ultrasonic microscopy has potential ability at the point of view of sensitivity to microstructural variation in materials during ser-

vice⁽¹⁾⁻⁽³⁾.

In this study Cr-Mo steel crept specimens with the microstructures simulated to heat affected zone (HAZ) and weld joint were investigated using the LSAW technique. Large-aperture-angle line-focus transducers to generate LSAW having each frequency around 10 MHz and 25 MHz on the material surface have been developed for evaluating creep damage. Scanning system using gap immersion technique to acquire LSAW signal over a wide area of material was also designed. The relations between the feature parameters of ultrasonic pulses of LSAW and the microstructural variation due to creep damage during service are discussed in this paper.

2. Creep Test Specimens

2.1 Test materials

The low alloy steel of 1.25Cr-0.5Mo, commonly utilized for high temperature components, was selected as an objective material of the investigation. To execute the fundamental study of creep damage of welds, simulated HAZ and welded joint test specimens (hereinafter called H-specimens and W-specimens respectively) were prepared.

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Fig. 1 Creep test specimen machined from welded joint plate

The simulated HAZ specimen of 1.25Cr-0.5Mo steel plates (19 mm thick) were manufactured by heating to the maximum temperature of 1280–1320°C, holding for 5 minutes and oil quenched. Post heat treatment was also conducted at a temperature of 640–680°C for 60 minutes. Two different dimensions of specimens were prepared. One was the special type specimen with the 12 mm square gauge section to be used for ultrasonic measurement and the other is the standard creep test specimen with the gauge section of 6 mm in diameter to obtain the strain-time relation. Twelve special type specimens and one standard creep specimen were machined out from the simulated HAZ plate. The standard creep specimen was designed in accordance with Japanese Industrial Standard (JIS).

The X-groove weld specimens of 1.25Cr-0.5Mo steel plates (19 mm thick) were also machined out from welded joint in the same way as the case of simulated HAZ mentioned above. Eight special type specimens and one standard creep specimen were machined out from the welded joint. The method how to machine the specimens is schematically illustrated in Fig. 1.

2.2 Creep tests

Accelerated creep tests were conducted at a stress of 76 MPa and a temperature of 600°C. In advance, three H-specimens and two W-specimens of special type were tested to obtain the each rupture time. It was confirmed that the averaged rupture times of H-specimen and W-specimen were around 2500 hours and 1500 hours, respectively. Based on the results of the rupture time, exposed time of creep test for each specimen was determined to make creep specimens with various degrees of damage so that creep life fractions of the creep specimens were ranging from 0.6–0.9. To obtain the creep curves of time versus strain for H-specimen and W-specimen, the standard creep test specimens with 6 mm diameter were exposed under the same creep test conditions.

The creep tests for nine H-specimens and six W-specimens of special type were executed under the creep conditions and interrupted at the specific time corresponding to creep life fractions of 0.6 to 0.9

Fig. 2 Creep strain as a function of creep time

within the averaged rupture time. Unexpectedly two W-specimens, however, were broken before the interrupted creep time.

The strains of each specimen were shown as a function of the interrupted time of creep test (creep life fraction) in Fig. 2. All data of the H-specimens plotted were close to the strain-time creep curve made by the standard creep specimen. On the other hand, in the case of W-specimen, all data are scattered and far from the creep curve for W-specimen. This was caused by the metallurgical inhomogeneity of weld joint which consists of weld metal, coarse grain region and fine grain region of HAZ and base metal. Accordingly, it is considered that the time of creep test is not appropriate to determine the degrees of creep damage in welds.

Then, the creep specimens prepared according to the above procedure were machined to rectangular with 10 mm square in cross section and 50 mm length for microstructural analysis and nondestructive evaluation.

2.3 Microstructural analysis

Scanning electron microscopy (SEM) was used to examine the degree of creep damage, since one of the most important indicators of creep damage is existence of voids and micro crack. For each creep specimens used in this study, the size of voids observed along grain boundaries by SEM with a magnification of 2000 was almost around 1 μm in diameter. In the case of H-specimens the number of voids tends to increased with the creep life fraction. Most of them were oriented perpendicular to stress applied and coalesced along grain boundaries. In the case of W-specimens, voids and cavities were observed mostly in HAZ and base metal adjacent to HAZ. The size and number of voids in W-specimens were not related to the creep life fraction because of the metallurgical inhomogeneity of welds. In this study, the results of the microstructural observation

were employed to define the degree of creep damage instead of creep test time corresponding to creep life fraction. The data obtained from LSAW technique were investigated comparing with the results of the microstructural observation.

3. Application of LSAW Technique

Although creep damages are likely to occur both near surface and inside body of materials, this study aimed to detect and evaluate the near surface creep damage which is very concerned in weld structure of high temperature component. As the damage almost occurs locally in the particular region such as heat affected zone of weldment, we examined the following techniques.

The specification and configuration of the transducers used for the examination are shown in Table 1 and Fig. 3, respectively. The line-focusing elements (nominal frequency: 10 MHz and 25 MHz) were made of PVDF (high polymer) having large-aperture-angle as shown in the figure⁽⁴⁾⁻⁽⁶⁾. Schematic drawing of experimental arrangement is shown in Fig. 4. When water path length is exactly adjusted to the radius of element curvature as shown in Fig. 4 (a), the maximum surface echo (S-echo) is obtained. On the contrary, when water path length is shorter than radius of element curvature as shown in Fig. 4 (b), two signals appear as shown in Fig. 4(c). The second signal (LSAW-echo) is the echo generated by following path (P-Q-R-S in Fig. 4(b)). As shown in the Fig. 4(b), a part of ultrasound emitted by transducer element propagates along the surface of test specimen obliquely and it is converted to LSAW at the interface (P-Q) when incident angle is the critical angle i_{CR} given by Eq. (1).

$$i_{CR} = \sin^{-1} \left(\frac{V_w}{V_L} \right) \quad (1)$$

Where V_w is sound velocity of longitudinal wave in water, V_L is the sound velocity of LSAW along the material surface. The LSAW propagates along the surface with leaking longitudinal wave into water (Q-R). The longitudinal wave impinging transducer element perpendicularly is received (R-S).

Table 1 Specification of transducers

Transducer type	Line-focusing
Nominal frequency	10MHz, 25MHz
Material of element	PVDF
Size of element	8×2mm
Aperture angle	90deg.
Focal distance	5mm

Fig. 3 Configuration of transducer

(a) Water distance = Focal distance

(b) Water distance < Focal distance

(c) LSAW echo in time domain and frequency domain

Fig. 4 Schematic explanation of LSAW technique

Power spectrum obtained by fast Fourier transformation (FFT) of LSAW echo is also shown in Fig. 4(c). Some feature parameters of ultrasonic wave both in time domain and in frequency domain as shown in the figure can be available for evaluating creep damage.

Transducer was scanned in water automatically at constant water path length over the each specimen surface. Each scanning area is 6×9 mm to avoid unexpected effects from side wall of the specimen and 864 waveforms of LSAW were acquired at every step of 0.25 mm as shown in Table 2. While transducer of 25 MHz was used for W-specimens to obtain data with high sensitivity and high resolution for creep damage, transducer of 10 MHz was used for H-specimens considering attenuation due to scattering because of coarse grains in microstructure of the material. The propagation direction of LSAW was set same as the direction of tensile load, because the

Table 2 Testing condition for acquiring data

Items	H-specimens	W-specimens
Nominal frequency of transducer	10MHz	25MHz
Sampling frequency	100MHz	400MHz
Scanning area	6×9 mm	6×9 mm
Scanning pitch	0.25mm	0.25mm
Water distance	$3.0 \mu\text{s}$	$3.0 \mu\text{s}$

features of LSAW are likely to be influenced when LSAW propagate across the grain boundary along which void or cavities were created.

4. Experimental Results

The first moment (gravity frequency) shown in Fig. 4 is one of the most important and available parameters for evaluating material degradation, because it is not affected by singular data in power spectrum irrelevant to test results. As typical examples of results, the C-scope distribution of the first moment of power spectrum (gravity frequency) obtained for three H-specimens with different degrees of damage, no void (virgin material), oriented voids and micro fissures, are illustrated in Fig. 5. The examples of microstructures for each specimen are also presented on the right side of the figure. The histograms of the first moment are shown in Fig. 6. The distribution of the first moment in the test area is shown in the figure. When creep voids are nucleated and coalesced, the first moment of LSAW shifted a bit to lower frequency. This is caused by attenuation of high frequency components of LSAW due to scattering at voids as discussed later.

Three W-specimens with different degrees of damage, no void (virgin material), oriented voids and localized micro-cracking along the grain boundary in HAZ, were examined by LSAW technique. The

Fig. 5 Test results (First moment of power spectrum) of *H-specimens* using LSAW technique and micrographs by SEM

results are shown in Fig. 7. In spite of the non-damaged specimen, the first moment of LSAW of weld metal is slightly lower than that of base metal as shown in Fig. 7(a) because of coarse grains in weld metal. The first moment of LSAW is slightly shifted to lower frequency in local area where oriented voids are located along grain boundary in HAZ as shown in Fig. 7(b). Localized micro cracks due to creep damage in HAZ make the first moment of LSAW lower predominantly as shown in Fig. 7(c).

The histograms of the first moment of LSAW in HAZ (two mm in width) are shown in Fig. 8. The

lower frequency components of the first moment representing damaged part as shown in the Fig. 7(b) and (c) increase. These results indicate that local damage occurs in HAZ.

5. Discussion

As shown in Figs. 5 and 6, the first moment of LSAW was changed depending on the degrees of creep damage. The creep damages observed by microscopy are classified to following stages⁽⁷⁾.

(a) No cavities

Fig. 6 Histograms of the first moment in *H*-specimens (simulated HAZ specimens)

Fig. 8 Histograms of the first moment in HAZ of *W*-specimens (welded joint specimens)

Fig. 7 Test results (First moment of power spectrum) of *W*-specimens using LSAW technique and micrographs by SEM

- (b) Isolated cavities
- (c) Oriented cavities (depending on direction of stress)
- (d) Micro-cracking
- (e) Macro-cracking

As the stages defined above are associated with creep life fraction as shown in Fig. 9, quantitative estimation of the stage of creep damage can be expected to be powerful means to predict the remaining life. One of the most important things in NDE for creep damage is the quantitative relations between microstructural change and feature parameters obtained from NDE technique. Particularly, weld joints, which contain weld metal, coarse grain HAZ, fine grain HAZ and base metal, have inhomogeneous mechanical properties and structures. As each portion of the weld joints has peculiar creep sensitivity, the degree of creep damage of a whole specimen could not be defined by one creep fracture time and local observation of microstructural change of the specimen should be considered. The influences of microstructural changes in material on ultrasonic characteristics are interpreted as follows.

When voids and/or fissures exist in material, they act as scatterer for incident wave (longitudinal and/or shear wave) and the wave attenuates due to scattering by scatterer. The attenuation coefficient can be written by

$$\alpha = \frac{1}{2} n_0 \gamma \quad (2)$$

where n_0 is the number of scatterers per unit volume (volume density) and γ is the total scattering cross section which is the ratio of the energy scattered out of wave by a single scatterer to the incident wave energy density. The scattering cross section for surface wave, however, has not been given theoretically. Taking into account that the surface wave involves the components of both longitudinal and shear wave, the total scattering cross section γ is tentatively given

by

$$\gamma = \int \frac{d\gamma}{d\Omega} d\Omega \quad (3)$$

where $d\gamma/d\Omega$ is differential scattering cross section and Ω is solid angle all around a scatterer.

While $d\gamma/d\Omega$ is proportional to the forth power of wave number for longitudinal and shear waves and also the square of shape factor of scatterer peculiar to each wave mode. The each shape factor is roughly proportional to the volume of scatterer, attenuation coefficient α is given by

$$\alpha \approx f^4 v^2 \quad (4)$$

where f is a frequency and v is a volume of voids and/or fissures. According to the relation of Eq.(4) as creep proceeds with the nucleation and growth of voids leading to the formation of fissures, the higher frequency components of wave do attenuate and then the first moment of power spectrum of received wave shifts to lower frequency.

In this study all LSAW signals in time domain having several feature parameters were acquired on the surface of specimen. It has been reported that material degradation such as intergranular corrosion and hydrogen attack causes high attenuation, decrease of velocity and shifting in power spectrum to lower frequency in ultrasonic characteristics^{(8),(9)}. The following tendencies are expected in crept materials, considering that the process of creep: starting from formation of dislocation substructure, transformation of carbide, nucleation of cavities, formation of oriented cavities, growing micro fissures and macro-cracking before rupture.

- (a) Amplitude of LSAW decreases.
- (b) Velocity of LSAW decreases.
- (c) Center frequency of LSAW becomes lower.
- (d) The first moment of power spectrum (gravity frequency) becomes lower.
- (e) High frequency component of LSAW attenuates.

Therefore, it can be said that LSAW technique has potential ability to be alternative method to microscopic observation.

6. Conclusion

The crept specimens fabricated by simulated HAZ and weld joint of Cr-Mo steel were investigated using the LSAW technique. The results that the ultrasonic characteristics were affected by microstructure deterioration due to creep were obtained. Particularly high frequency components of LSAW decrease correlated with the formation of creep voids and fissures. Ultrasonic spectroscopy technique can be expected to be available for deducing the state of creep quantitatively on the basis of the changes in

Fig. 9 Changes in Microstructure with progress of creep damage

ultrasonic propagation characteristics due to microstructure deterioration under long-term operation at high temperature.

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