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Optimization of monitoring method for CGR measurement of XM-19

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Crack growth by stress corrosion cracking (SCC) in stainless steels is an important issue not only for fission reactors but also for fusion reactors. In Japan, the continuous operation of the plants having cracks in their in-core components has become possible since 2004, which is based on a crack growth analysis by SCC crack growth rate (CGR). However, the collection of SCC CGR data of steels used in the reactors has not been completed yet. From those backgrounds, our research project for the CGR measurement of XM-19 which is a high strength stainless steel used for a tie-rod of the core-shroud was started about five years ago. A potential drop method (PDM) using reverse current was applied to the CGR monitoring. However, a large scattering of the daily data was observed in an early stage. The data scattering was suppressed later by optimization of current reverse frequency and our monitoring system achieved 1.5 micro-meter resolution of crack depth. CGR of XM-19 ranged 1～2×10^{-10} m/s under the BWR normal water condition, which was higher than that of solution annealed 316 stainless steel.

Keywords: stress corrosion cracking, crack growth rate, potential drop method, reverse current, noise reduction, light water reactor

1. Introduction

Stress corrosion cracking (SCC) is one of main degradation phenomena seen in the components used under a pure water environment. Japan Society of Mechanical Engineering Fitness-For-Service (JSME FFS) code has been developed for the judgment of structural integrity of cracked components of Light Water Reactor since 2004 [1]. JSME FFS code has a data set of SCC crack growth rate (CGR) of type 304 and 316 stainless steels for crack growth analysis. SCC CGR is a great concern of plant owner because the future operation including continuous use, repair and replacement of the component will be judged by the crack growth analysis based on CGR data.

The mechanism of SCC has not been fully understood and the theoretical formulization [2] has not been completed because many parameters such as stress level, water purity and material condition have effects on CGR. Moreover, SCC CGR is usually so low (at most 10^{-9} m/s) that the reliable data collection takes very long time. In the experimental aspect, the use of experiment apparatus needs some practice because the apparatus is composed of many valves, pumps and instruments for water quality measurement etc. The establishments of water quality control procedure and of CGR monitoring system are the most important tasks to be adjusted before the experiment. Especially, the system should be build by the users because apparatus makers usually leave the system for users. Furthermore, from the view point of industrial standard, few guidelines for CGR measurement are available. Some problems relating data collecting manner are suggested by a world authority on SCC in thesis [3] and actually our system didn't work well in an early stage.

The tie-rod repair method has been used for the core shroud of BWR (Boiling Water Reactor). The method is to set four bars around the shroud and to link top and bottom of shroud by the bar, which prevents the shroud from splitting at the moment of seismic load. Tie-rod is composed of some parts made of Inconel alloy X-750 and XM-19. Both materials are known to be highly resistant to SCC occurrence [4]. However, SCC CGR data set has not been collected, especially for XM-19.

From the above background, we started the experimental study on CGR measurement about five years ago. Five years were consumed mainly by building of CGR monitor system. Therefore, the details are introduced with experimental result of crack growth measurement of XM-19 in this paper.

2. Experimental

2.1 CGR measurement apparatus

Figure 1 shows the schematic diagram of SCC CGR measurement apparatus. The water reserved in a tank is supplied to an autoclave through a pipe line with a high-pressure pump and a pre-heater. The pressure of water in autoclave is controlled by a pressure adjustable valve at the downstream. The temperature of water in autoclave is controlled by a pre-heater and a band-heater of the autoclave. CGR monitoring system is composed of a lead wire, a direct current source and a voltage meter. Figure 2 shows the detail of the monitor system. The lead wire is made of Pt because the corrosion of wire can make noise.

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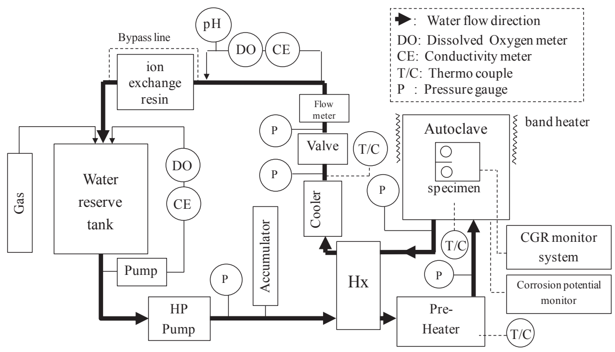

Fig.1 Schematic drawing of the apparatus

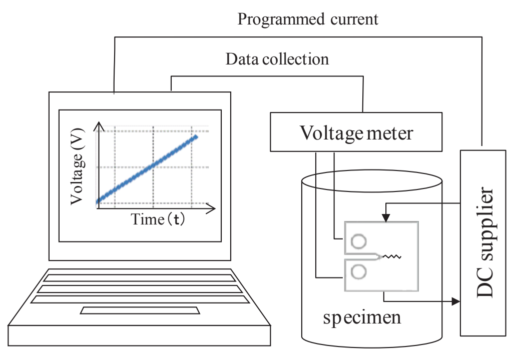

Fig.2 Crack growth monitor system

2.2 Reverse current PDM (Potential drop method)

Potential drop method (PDM) with reversed current has been applied to the CGR measurement. PDM is the method to detect the increase in voltage due to the increase in resistivity. The resistivity increase is caused by decrease in cross section of specimen which is due to crack growth. The current reverse is one of techniques to cancel the electromotive force. The principle of cancelling is to utilize the characteristics of electromotive force which is not affected by current direction (Fig.3). However, the frequency of the current reverse is important because the origin of force is time-dependent event in our laboratory, which is simply depicted in Fig.4. This is considered to be due to the room temperature control problem, which may be specific to the laboratory.

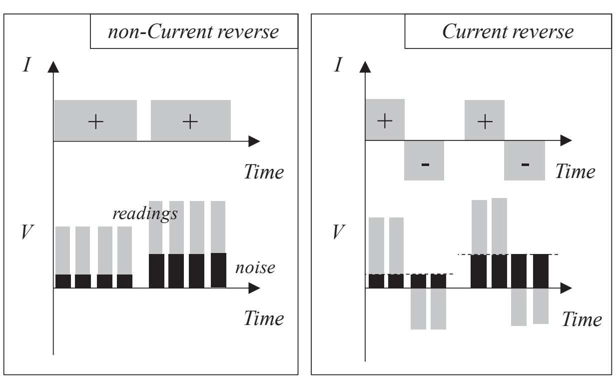

Fig.3 Principle of current reverse method

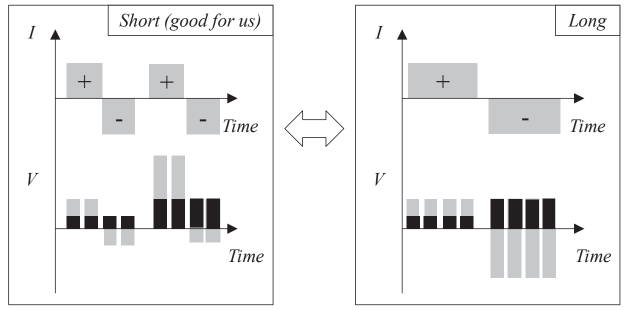

Fig.4 Optimization of the current reverse frequency for our laboratory

2.3 CGR measurement of XM-19

A 19% cold worked plate was supplied from GE in US for CT specimens of SCC experiment. Table 1 is the chemical composition and Table 2 is the mechanical properties of XM-19. The plate was cut into 0.5TCT specimen (Fig.5) and approximately 1 mm pre-crack was introduced in air at Kobe Material Testing Group in Japan. After the CT specimen was installed in our autoclave, the environmental fatigue crack was introduced by fatigue load in hot water. This is the manner to change crack growth from fatigue mode to SCC mode. The environmental fatigue load was started from low with high stress ratio ($\sigma_{max}/\sigma_{min}$), followed by high with low stress ratio. This manner was used not to introduce plastic deformation at crack tip of the specimen. After the environmental fatigue loading, the loading mode was changed to constant, static SCC mode. If the monitored crack seemed to stop under constant load, we repeated the manner from fatigue mode to static mode.

The validity of crack growth data was judged by referring a Forum of Japan society of corrosion engineering [5]. The specimen size used for CGR measurement test can be valid if the following equations are satisfied. K value was confirmed to be acceptable up to 36MP$\sqrt{}$m for this study.

$$B > 0.5(K/\sigma_y)^2, \quad (1)$$

where B is specimen thickness (m), K is stress intensity (MPa$\sqrt{}$m) and σ_y is 0.2% proof stress (MPa) at test temperature.

$$W\text{-}a \geqq 4/\pi\,(K/\sigma_y)^2 \quad (2)$$

where W is specimen width (m) and a is crack length (m).

Table 1 Chemical composition of XM-19

Mo	C	Nb	Cr	Fe	Mn	Ni	Si
2.2	0.03	0.2	20.76	58.93	4.59	12.82	0.39

Table 2 Mechanical properties of cold worked XM-19

Temperature	$\sigma_{y0.2\%}$ (MPa)	σ_{ULT} (MPa)	ε_f (%)
24℃	891	993	22.1
288℃	690	790	14.5

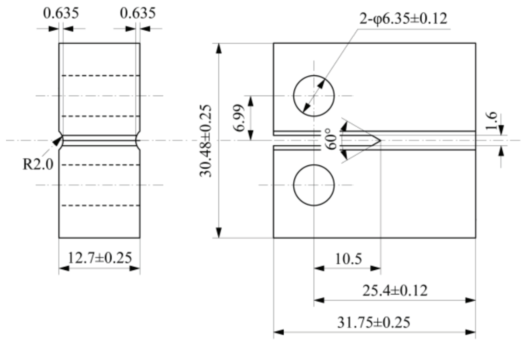

Fig.5 Schematic drawing of 0.5TCT specimen

3. Results and discussion

3.1 CGR monitor system

The voltage fluctuation under non-loading condition was measured under various conditions to confirm the data quality of our CGR monitor system. In an early stage of confirmation, we considered that the current reverse frequency should be low because we believed that the number of readings should be large from a view point of statistics. Figure 6 is a typical low frequency pattern of reverse current, which was applied in an early stage to our CGR measurement. However, we noticed that too low reverse frequency would be worse because the noise in our monitor system was time-dependent. Figure 7 is the optimized high-frequency reverse pattern for our system. The voltage readings during a few seconds after the start of the current discharge are cleared to eliminate the effect of ripple noise on the readings. Figure 8 shows the relation between the voltage fluctuation and total time (which corresponds to total number of readings). The voltage fluctuation in the case of high-frequency is low compared with that in the case of low-frequency. The result in the case of Fig.6 is depicted in this figure, indicating that the volume fluctuation after the improvement becomes one-sixth compared with that before the improvement. The increase in the number of readings corresponds to the increase in total measurement time and suppresses the fluctuation, which is reasonable from statistical viewpoint.

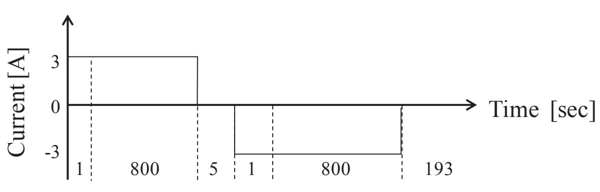

Fig.6 Low frequency pattern

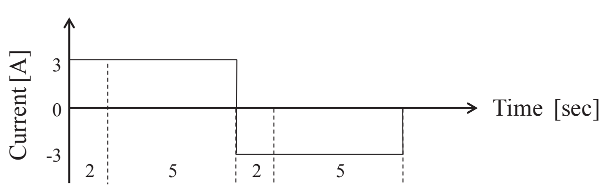

Fig.7 High frequency pattern

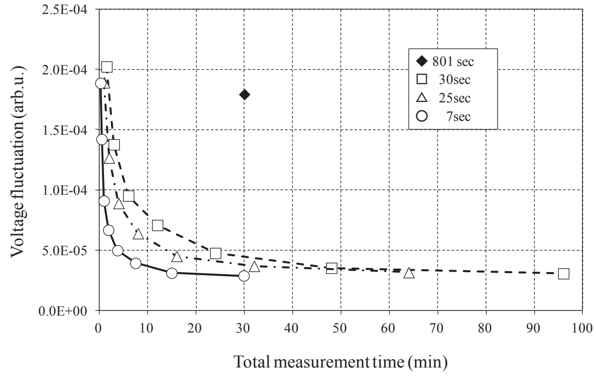

Fig.8 Relation of current pattern and voltage fluctuation

Figure 9 is the crack length fluctuation of the specimen measured prior to CGR measurement under load free condition. The interval of two dashed lines (statistical $\pm 1\sigma$, 68% confidence interval), which corresponds to the crack length resolution of our monitor system, is less than 1.5 μm. As a result of a private communication with a world authority on SCC, the resolution of crack is about 1 μm at best. Considering that the resolution was 100 μm order in the case of Fig.6, the final resolution (1.5 μm) of our monitor system could be a great progress. The cause of fluctuation in crack length was considered to be the fluctuation of water temperature in the autoclave due to the room temperature control problem.

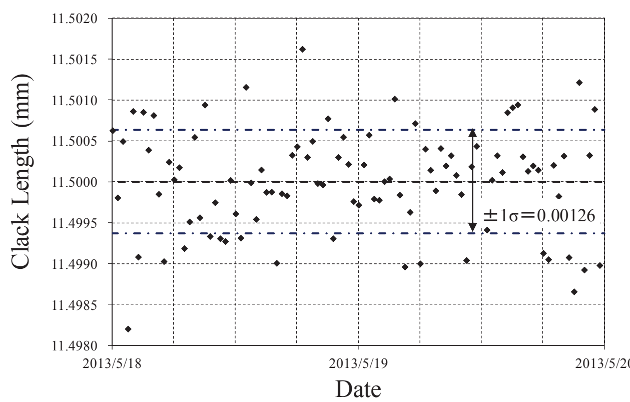

Fig.9 The fluctuation of crack length reading prior to the CGR measurement (Load free)

3.2 CGR of XM-19

Figure 10 shows the result of crack growth behavior of XM-19. The water in the water reserve tank was opened to the ambient air and the oxygen was thought to be dissolved at saturated solubility, therefore, the measured dissolved oxygen (DO) was about 7～8 ppm during the CGR test. In the middle of September, the apparatus was once shutdown due to a planned power outage. The specimen was unloaded and the autoclave was cooled down to room temperature before the outage not to introduce plastic deformation at crack tip of the specimen. After the outage, the stress and the temperature conditions were returned to the same condition as that before the outage. The crack growth behavior before the outage is linear with the time and the trend is almost same as that after the outage, showing absence of the effect of the outage. Two regions where crack growth behaviors became relatively stable were selected for decision of CGRs. Figure 11 is a part of the fracture surface of specimen after crack opening. This microscope observation indicates that the fracture surface of SCC is inter-granular type, which enabled us to confirm the total crack length of SCC. As the result of confirmation, the relation between the voltage reading and the crack length was obtained and used to draw Figs.9 and 10. The rough estimation of the ratio of actual length and measured voltage was 40 μ m/ μ V. The crack length resolution of our CGR monitor system during crack growth was approximately 30nV, which corresponds to 1.2 μ m and is the same order as that measured prior to the CGR test.

Figure 12 is the summary of the result of this work, which is the comparison between plots of this work and the deposition lines of sensitized 304 and solution annealed 316 stainless steel in JSME FFS code. In addition to the plots of this work, the results of previous work (0% cold worked XM-19) are also plotted for a reference. The water electrical conductivity at the inlet of autoclave was less than 0.2 μ S/cm, which was almost the same value as that of a actual plant. On the other hand, the conductivity at the outlet of autoclave ranged 0.5～0.6 μ S/cm. CGRs data taken in this study, therefore, may be conservative because the higher the electrical conductivity becomes, the faster the CGR becomes in hot water [6]. Low conductivity less than 0.2 μ S/cm at the inlet and high conductivity exceeding 0.5 μ S/cm at the outlet were also seen during CGR measurement of 0% cold worked specimen. Therefore, the discussion about the effect of cold work on CGR is considered to be possible. The fact that the CGR of 0% cold worked specimen is almost same as that of solution annealed 316 stainless steel, as shown in Fig.11, seems to support this consideration. From the above consideration, the difference in CGRs of XM-19 is thought to be caused by cold work as pointed out by some literatures [7].

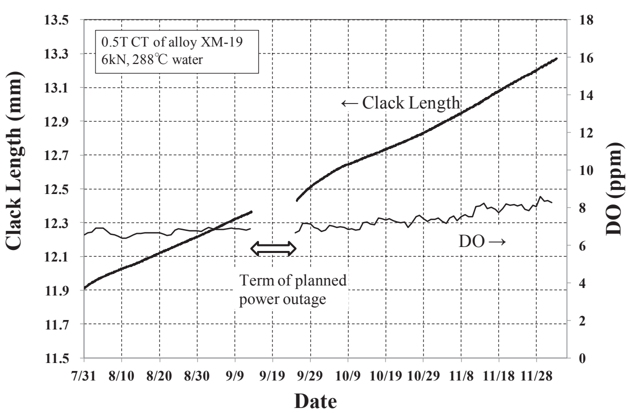

Fig.10 Crack growth behavior of XM-19

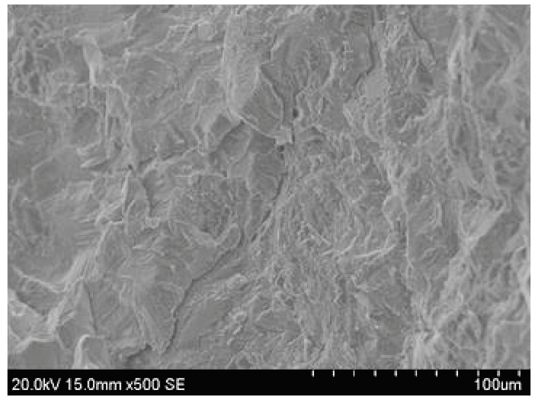

Fig.11 Fracture surface of specimen

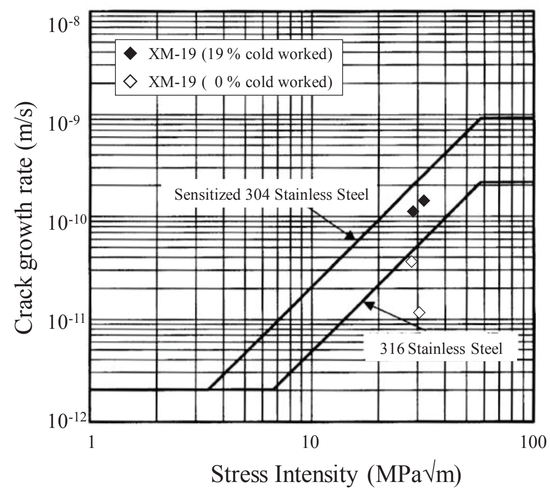

Fig.12 Comparison between JSME and this study

4. Conclusion

The reverse current frequency in PDM was optimized for our monitor system. As the result of optimization, the crack length resolution became 1.5 μ m, which is comparable to the apparatuses of major institutes.

SCC CGR of XM-19 was measured by the optimized monitor system. The CGRs were 1～2×10^{-10} m/s at stress intensity of 30 MPa$\sqrt{}$m and deposited above the line of 316 SS in JSME FFS code. The comparison in CGR between 0% and 19% cold worked XM-19 showed the effect of cold work on CGR.

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