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Residual Life-Time Evaluation Method Using Instrumented Indentation Test

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Abstract. Predicting the residual life of a structure is an essential issue in structure management. Many researchers have used different methods to predict structure lifetimes, such as the creep rupture test. However, this test is costly and time-consuming, and since it is also destructive, an unused specimen must be tested rather than an actual specimen in use. The instrumented indentation test (IIT), on the other hand, is easier and faster than conventional test methods, most important of all, it is a non-destructive method to obtain mechanical properties that can be performed on the actual structure in use. In this study, we obtained mechanical properties of a SA213-T23 tube material for a thermal power plant degraded for 1~2,000 hours at high temperature and observed the degradation by analyzing the microstructure. We found a relation between the Larson-Miller Parameter (LMP) and degradation tensile properties considering the temperature and degradation time and suggested a method to predict the residual life by applying a failure criterion. Also, we confirmed that our interaction formula and the residual life are reasonable by comparison with statistical rupture time data from materials that have in fact degraded.

Introduction

Over the long-term operation of high-temperature facilities such as power plants, the performance of a structure can change from its initial state due to aging and degradation. Therefore, timely maintenance and replacement of facilities are clearly very important. Much work has been done on establishing proper replacement times. And, through these efforts, such test methods as the creep rupture test [1-4] have been developed and Larson-Miller parameter (LMP) has been established as a lifetime assessment method that takes into consideration both temperature and duration of use. [5-7]

However, the creep rupture test must be performed under many different temperature and stress conditions, making it both time-consuming and expensive. Also, since it is a destructive method, it is difficult to obtain the specimens in their in-service state. In order to overcome these problems, some research has been done on predicting lifetime using a hardness test, which has fewer specimen constraints. [8] However, although hardness can be evaluated quantitatively, hardness testing also has limitations: it lacks physical meaning as a mechanical property and cannot predict rupture time quantitatively, as rupture does not occur.

Meanwhile, instrumented indentation testing has recently emerged as an alternative. Instrumented indentation test is a kind of hardness test machine which can express load-depth curve during indentation process. Tensile property measurement method by IIT has been developed for the past few decades [9-12] and has now been standardized in ISO/TR 29381. [13] And, because IIT can be used for in-service structures, it is utilized in situ where degradation occurs in nuclear power plants and gas-oil pipelines.

In the present study, we discuss a test method to evaluate the residual life of a high-temperature structural material based on degradation flow characteristics. Our specimen was exposed to a high temperature for a long time, obtained the Larson-Miller parameter and estimated degradation tensile properties in a non-destructive way using IIT. In addition, we found a relation between the Larson-Miller parameter and tensile properties and tried to predict the residual lifetime by applying our failure criterion.

Indentation Lifetime Estimation

In attempting to assess the lifetime of a high-temperature structural material based on the flow characteristics of degraded material using instrumented indentation testing. We obtained the Larson-Miller Parameter of specimen heat treated for various duration under high temperature and estimated the degraded material properties using IIT. It is difficult to express the LMP method, which can assess residual life, using material properties obtained by indentation. In particular, since rupture strength cannot be obtained using a method of assessing tensile properties based on ISO/TR29381, it is necessary to find a parameter that can replace it. We attempted to express the resistance to plastic collapse in a process in which final plastic collapse occurs together with plastic deformation when the stress exceeds the yield strength. [14,15]

$$L_r = \frac{\sigma_{ref}}{\sigma_Y} \tag{1}$$

where σ_{ref} is the applied stress and σ_Y is the yield strength. The value of L_r increases as stress applied to the structure increases. When the applied stress reaches σ_Y, plastic collapse occurs. According to the failure analysis method, σ_{ref} of plastic collapse is expressed as σ_{flow}, as follows;

$$L_{r,max} = \frac{\sigma_{flow}}{\sigma_Y} = \frac{(\sigma_Y + \sigma_U)/2}{\sigma_Y} \tag{2}$$

(σ_U = ultimate tensile strength)

We then assessed residual life by comparing L_r from this calculation to the API (American Petroleum Institute) rupture estimation standards (L_r <1.25, failure criterion).[16]

Note that, the effect of applied stress, major variable in assessing residual lifetime in the creep rupture test, is not considered in this model, since research in indentation theory shows that indentation tensile properties are not relevant to applied stress. [17] Instead, we obtained the relation with the lifetime curve through yield strength, time and temperature factors in instrumented indentation tests, and determine reasonable value for the lifetime and replacement time.

Experiments

SA213-T23 material commonly used for boiler tubes, is used in this study. Specimens were obtained by quadrisecting a tube of dimensions 51mm × 8.5mm (outer diameter × thickness) × 100mm towards the circumference. Table 1 shows the chemical composition. Accelerated degradation was done at 600°C and at 650°C, which does not cause the austenitic phase transformation, from 1 hour to 2,000 hours.

Table 1. Chemical composition of SA213-T23 (wt%)

Material	C	Si	Mn	Cr	Mo	V	Nb	W
SA213-T23	0.06	0.20	0.45	2.25	0.1	0.25	0.05	1.6

An Instron 5584 (Fig 1. (a)) universal dynamic test machine was used for the tensile test, and the specimen was precisely machined according to ASTM A370.Our results are the average of five tensile tests at a speed of 1mm/min as a result.

For instrumented indentation testing, AIS3000 equipment (Frontics Inc, Fig 1. (b)) was used, and instrumented indentation testing was performed 15 times to the depth of 150µm using an indenter of 0.25mm radius. Following ISO/TR 29381, the unloading rate was 50%, indentation speed was 0.03mm/min, and we maintained the maximum load for 0.5s. The specimen was made into blocks of 20mm × 20mm × 10mm size and the surfaces were ground using SiC paper from #220 to #2200.

For microstructure observation, we used a laboratory-type optical microscope (Nikon, LV-110ND) . In order to observe the structure, the surface was polished up to 1µm using diamond paste after the grinding on SiC paper. To observe the structure, the surface was etched by mixing 45ml of glycerin, 15ml of nitric acid and 30ml of hydrochloric acid, and cleaned for 2mins and 30secs in alcohol.

Fig. 1. Test machines (a) Instron 5584 (Left) , (b) AIS3000 (Right)

Results and Discussion

In order to explore whether tensile properties from instrumented indentation testing can be used to assess residual life, we compared yield strength and tensile strength from tensile testing with those from instrumented indentation testing. As shown in Figure 2, both yield strength and tensile strength match within 15%. At high temperature conditions, the change of tensile properties due to degradation can be confirmed, Figure 3 shows the microstructure results.

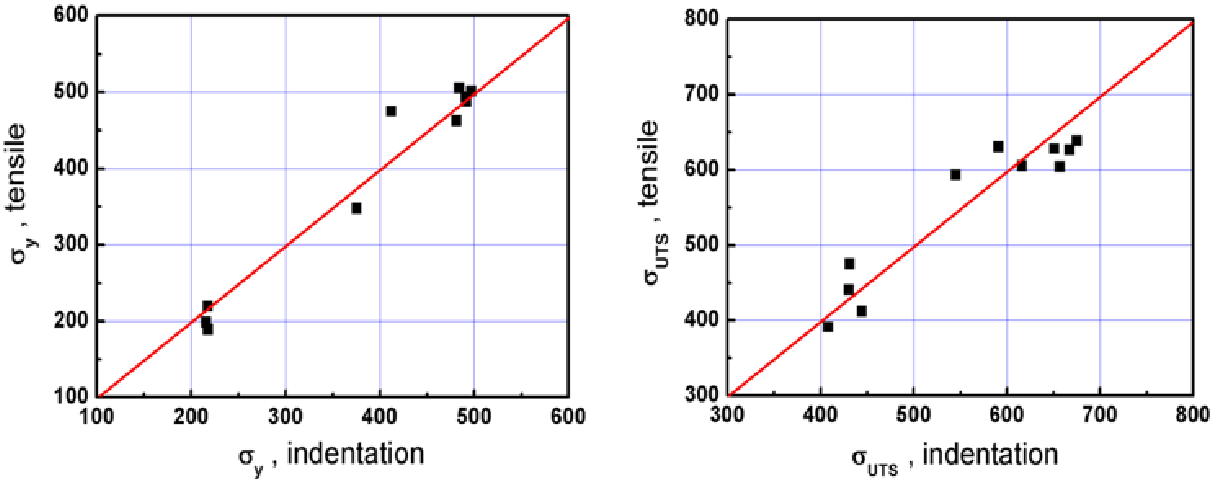

Fig. 2. Tensile properties of SA213-T23 as measured by uniaxial tensile tests and instrumented indentation tests yield strength (left) and ultimate tensile strength (right)

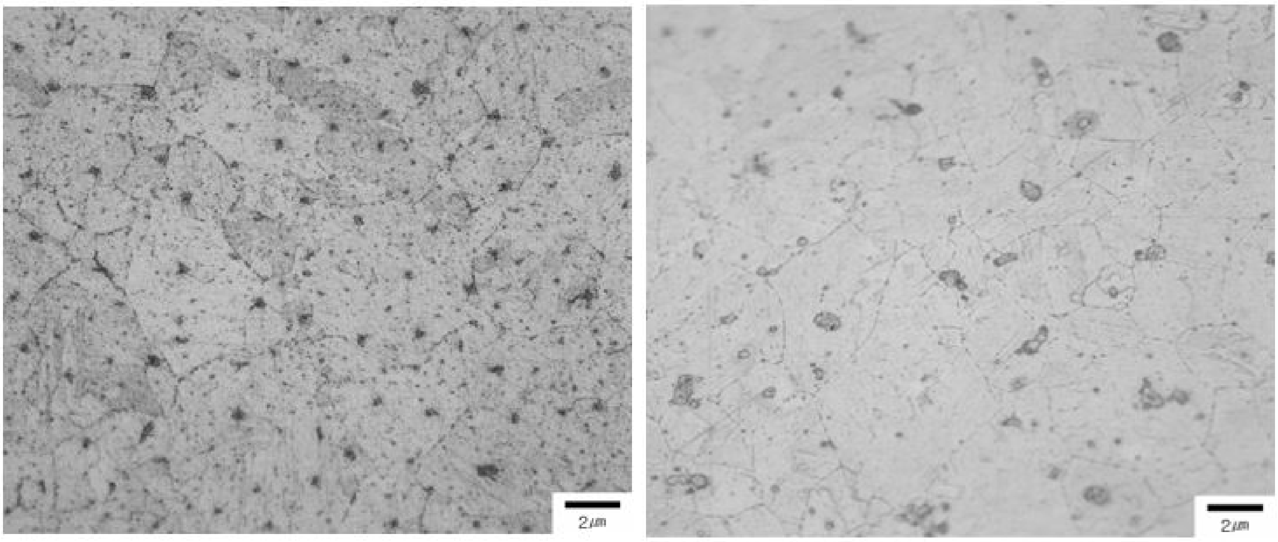

Fig 3. SA213-T23 microstructure degraded at 650°C
for 1 hour (left) and 1000 hours (right)

The microstructure of SA213-T23 consists primary of white alpha ferrite and black pearlite structure. Also, coarse carbide has grown as degradation continued under heat treatment, from this, reduction in strength is inferred.

The change in yield strength according to LMP is expressed as shown in the Figure 4. In this study, we used value of 20 as a constant C. The orthogonal polynomial approximation and the linear regression method were used to obtain the curves corresponding to the experimental results, and the polynomial fitting method was selected as the curve that best matches the experimental results.

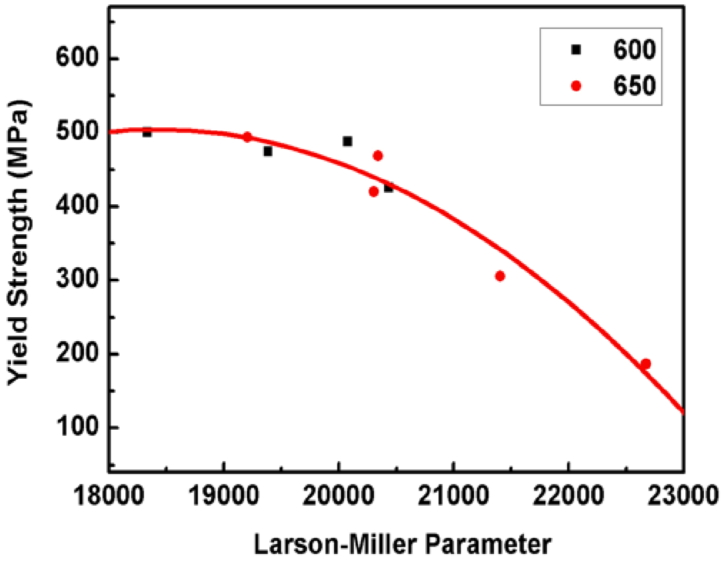

Fig. 4. Master curve for the degradation of yield strength for SA213-T23

The material specification suggested in the standards was adopted as the failure criterion mentioned above. The material specification for SA213-T23 in ASME Sec. II as follows; [18]

Table 2. The requirement for tensile strength in previous standard code

Material	Standard	Yield Strength (MPa)	Ultimate Tensile Strength (MPa)	Elongation (%)
SA213-T23	ASME Sec.II	400	510	20

Calculating the values in Table 2 for the failure criteria mentioned above, L_r value of 1.1375 can be obtained, which is smaller than the standard of 1.25. Thus, a yield strength value suggested in standard can be proposed to satisfy the failure criterion 1.25, and the residual life time of 372,156 hours was evaluated by applying it to Fig. 4.

In order to verify the assessment method suggested here, it was compared with Cr-Mo steel life evaluation which is similar to that of SA213-T23 material reported by Ray and Lee et al. [19,20] and to the method the results of the X20Cr-Mo-V study in Kim et al. [21] It can be seen that in both cases, the results agree within a reasonable range of error.

Nevertheless, further research results are needed for direct field application of this study. First, many kinds of materials are exposed to high temperatures in thermal power plant, their degradation mechanisms differ, and all must be explored in the research.

Also, our specimens were at temperature for only up to 2,000 hours, the degradation must be observed for a longer time so as clearly to identify the point at which actual fracture occurs. Moreover, if data can be obtained by setting the degradation time to more detailed conditions, it is expected that the data in Figure 4. can be expressed more precisely so that more accurate lifetime prediction is possible.

Conclusions

This study proposes a IIT lifetime prediction method for degraded in-service structures.

1. Tensile and instrumented indentation test were performed on boiler tube materials degraded from 1 to 2,000 hours, and the tensile properties evaluated were similar.
2. Yield strength and tensile strength were confirmed to decrease with degradation time, and microstructural analysis identified coarse carbide structures was observed in pearlite structure in SA213-T23 material.
3. Correlations with LMP were derived the yield strength evaluation results obtained from the indentation test. The failure criterion was introduced from API plastic collapse and ASME (American Society of Mechanical Engineers) material specification. The lifetime predictions compared to those in other studies and are considered reasonable.

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