Life Extension of Creep Damaged Low Alloy Steel Welds by Regenerative Heat Treatment

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Weldments in high-energy piping of fossil power plants are known to suffer extensive creep damage over the course of long-term operations. This damage appears in the form of macro cracks, which result from the formation and linkage of creep cavities at the grain boundaries. It has been reported that creep cavities become sintered when subjected to compressive stress at high temperatures, and, if they could be eliminated before they develop into macro cracks, it was considered that this would enable life extension of components. This paper presents a process of regenerative heat treatment for the life extension of low alloy steel weldments by means in localized high-temperature heating of deteriorated locations. It is shown that recovery of creep life is attained as a result of high temperature compression tests and heat cycles around the A3 transformation temperature.

KEY WORDS: creep; low alloy steel; heat treatment; recrystallization; grain boundary; maintenance.

1. Introduction

Several examples of weldment failures in high-energy piping subjected to long-term operation have been reported,1) and the maintenance of such components is a major concern for electric power utilities. In this context, in addition to creep life evaluation technology,2) about which considerable research has been made, life extension technology is also needed. Weldments in Cr–Mo steel, commonly used for high energy piping, undergo microstructural changes early in life, through the recovery of martensitic lath structure. From the middle to late stages of life, creep cavities initiate at the grain boundaries and develop macro crack into resulting from the linkage of these cavities.3) Accordingly, at the stage of microscopic damage (i.e., prior to the initiation of macro-cracks), the elimination or removal of the accumulated damage facilitates the life extension of components.

Several research reports4–8) indicate that cavities, which are the direct cause of creep fracture, become sintered and disappear when subjected to high-temperature, long-term heating. In particular, Shinya et al. have undertaken detailed investigation in austenitic stainless steel7,8) and shown that the application of compressive stress at a high temperature serves to promote the sintering of cavities. Taking advantage of essentially the same principle, practical regenerative technology has been developed9) whereby Ni-based super alloy gas turbine blades are brought to the manufacturing facility for Hot Isostatic Pressing (HIP) treatment. Thus, if this technology can be used to actively rejuvenate damage and regenerate material at the stage of microscopic damage (i.e., prior to the occurrence of macro-cracks), life extension of weldments in high energy piping could be achieved. However, there are few research examples dealing with ferritic heat-resistant steel, and there has been no consideration at all of regenerative technology for large-scale components such as high energy piping, which cannot be easily taken off-site for factory processing.

The regions subjected to the greatest damage in high energy piping weldments in actual installations are known to be heat affected zones (HAZ), which exhibit a martensite structure having coarse grains due to the influence of heat during welding. When these regions are exposed to long-term, high-temperature service, they may be undergone metallurgical deterioration such as the precipitation of carbides and the recovery of dislocation structures, along with a higher crack propagation rate than that for un-serviced material, due mainly to the formation of cavities at the grain boundaries. Consequently, along with heating the affected regions beyond the A3 transformation temperature so as to change the HAZ microstructure from martensite to ferrite (equivalent to base metal) for improved ductility, it was considered that a greater life-extending effect could be achieved by simultaneously realigning the grain boundaries in order to contain the cavities within the grains and thereby slow down the rate of crack progress.

The objective of this paper is to aim at life extension for high energy piping weldments in thermal power plants and to consider the possibility of damage recovery for low alloy steel weldments by means of regenerative heat treatment with cavity sintering and recrystallization heat treatment such as heat cycle around the A3 transformation temperature.
2. Specimen and Experimental Procedure

2.1. High Temperature Compression Test

In order to quantitatively ascertain the effect on cavity sintering under the stress field generated by induction heating, creep-deteriorated material exposed to long-term service in an actual component was subjected to high temperature compression testing. The test material was from a main steam piping weldment of 2.25Cr–1Mo steel that had been serviced for approximately 256 000 h in a thermal power boiler, and which had been removed due to creep crack formation in the HAZ. Round bar test specimens were cut, having a diameter of 16 mm and a gauge length of 15 mm, such that the fusion line from the crack tip was positioned at the center of the specimen.

Specimens were set in a Survopulser testing machine, with a spirally wound inductive heating coil employed for heating to the designated temperature, after which constant rate compressive strain load testing was performed. The test conditions are shown in Table 1. Three sets of test conditions were selected, consisting of those for maximum generated stress, those for maximum generated strain, and a intermediate between the these two.

Here, strain rate $\dot{\varepsilon}$ (% · S⁻¹) is calculated according to the formula below.

$$\dot{\varepsilon} = k \sigma^n \left(\frac{211}{T}\right)$$

where, $k$ is a factor independent of temperature, $n$ is stress exponent, there are defined by $k = 10^{(21 - (27.0726 \times 10^3)/T)}$, $n = (5.186 \times 10^3)/T$ and $T$ is the absolute temperature.

The effect of cavity sintering generated by the high temperature compression test was investigated through microstructural observation of the specimen before and after testing, and the density of creep cavity was measured using the method described before for the quantification of the amount of cavity formation within a given area.

2.2. Recrystallization Heat Treatment

The test material was 1Cr steel (SA387-B) that had undergone approximately 246 000 h of service as high temperature reheat piping in a thermal power plant boiler. It was removed from the outer surface coarse-grained HAZ after the life consumption level of 75%. Test specimens with 7 mm diameter and 30 mm gauge length were taken from this longitudinal weld. Specimens were set in the induction heating equipment (having a spiral coil), and the recrystallization heat treatment was performed.

Table 2 documents conditions for the recrystallization heat treatment. Case 1 consisted of heating to the standard normalizing temperature of 1 193 K, followed by air cooling to room temperature. Designating case 1 as one cycle treatment, case 2 involved three cycles and case 3 involved five cycles. In case 4, a heating and cooling was repeated to within $\pm 50$ K of the transformation point, with three cycles between 1 203 and 1 103 K.

Outer surface replicas were taken from the test specimens after recrystallization heat treatment, and the optical microstructure was observed. The effect of each set of test cases was examined in comparison with untreated material.

2.3. Creep Crack Propagation Testing of the Recrystallization Heat Treatment Specimen

The test specimen of 2.25Cr–1Mo steel removed from an actual component, the same as in the high temperature compression test. A plate of approximately 60×60×15 mm was cut from the same weldment at a location corresponding to the creep crack tip, and used for the specimen. In order to prevent extreme heating of the test specimen edges during induction heating, the specimen was affixed to a carbon steel plate by welding, after which only the location of crack progress was subjected to induction heating on both the front and back sides in the round-type coil. Test condition of case 4 for the recrystallization heat treatment described above was adopted. Figure 1 shows the external appearance of the test specimen after recrystallization heat treatment testing. After recrystallization heat treatment, the test specimen was cut such that the orientation of crack progress can be seen to be parallel to the weld line. Then, the specimen was subjected to creep crack propagation testing with a load of 1 667 N at 923 K. A replica was also

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**Table 1.** High temperature compression test conditions.

| Condition selection criteria | Stress [MPa] | Temp. [K] | Strain rate determined from temp. and stress [h⁻¹] | Test conditions |
|-----------------------------|-------------|-----------|--------------------------------------------|----------------|
| At time of maximum generated stress | 332.4       | 693       | $2.3 \times 10^{-7}$                        | 0.319, 0.307   |
| Temp. between those of conditions 1 and 3 | 10.7        | 1213      | $6.94 \times 10^{-2}$                      | 0.959, 0.344   |
| At time of max. strain and max. strain rate | 9.5         | 1253      | $2.03 \times 10^{-1}$                      | 1.040, 0.386   |

*Stress, strain rate, and strain are taken to be positive in the direction of compression.

**Table 2.** Recrystallization heat treatment test conditions.

| Heating temp (K) | No. of heating and cooling cycle | Remarks | Specimen No. |
|------------------|---------------------------------|---------|--------------|
| 1) -             | 0                               | -       | Untreated material |
| 2) 1193          | 1                               | Air cooled at room temp. after heating | Case 1 |
| 3) 1193*         | Multiple times                  | Same as above | Case 2 |
|                  | 5                               | Same as above | Case 3 |
|                  | 3                               | Heat cycles of around the A₃ transformation point (1203=1103K) | Case 4 |

* Heating to 1203K in case 4 only
taken of the surface of the same specimen after recrystallization heat treatment. Microstructural examination confirmed that microstructural change had taken place by the treatment. For a comparison purpose, creep crack propagation testing was also performed on damaged material that had not been treated, and the damage recovery effect of the recrystallization heat treatment was further investigated.

3. Test Results

3.1. High Temperature Compression Test

Figure 2 shows optical micrographs before and after high temperature compression testing for each set of test conditions. In each case, the number of cavities is reduced when the micrographs are compared between before and after the tests. The measurement of cavity density revealed that cavities reduced from 4 000 to 2 469/mm² with a reduction ratio of 40% for condition 1 with a maximum stress achieved at 693 K. This results in improving life recovery of 11%. Similarly, for condition 2 at 1 213 K, cavities reduced from 4 427 to 2 268/mm², and for condition 3 generating a maximum strain at 1 253 K, cavities reduced from 3 954 to 1 432/mm². The measurements for conditions 2 and 3 correspond to cavity reduction ratio of 48% and 64%, respectively, and converted to life recovery of 14% and 21%. Thus, the cavity sintering can be effective in the order of condition 3, 2 and 1, corresponding to the order of high heating temperature and large strain.

Cavity sintering, as previously noted, is considered to be related to temperature and the strain in the vicinity of the cavities. That is, given that the diffusion rate is faster with higher temperature, the atoms in the vicinity of a cavity become easier to move, and the occurrence of compressive strain in this state facilitates cavity sintering. This explains why the cavity reduction ratio is greater in the order of high temperature and large strain.

It should be noted that, while the microstructure after high temperature compression testing changes to ferrite-bainite under conditions 2 and 3, where the $A_3$ transforma-
tion temperature is exceeded, recovery of the deteriorated microstructure is not observed in the case of condition 1, where the heating temperature of 693 K is under the $A_3$ transformation temperature. Since microstructural recovery is thought to influence life-extension of the deteriorated weldment, this is further described below in details.

3.2. Recrystallization Heat Treatment Test

Figure 3 shows representative optical microstructures after recrystallization heat treatment, together with that of untreated material. The untreated material exhibits a coarse-grained HAZ microstructure, consisting of deteriorated martensite in which the lath structure has disappeared and characterized by coarse grains. In contrast, the microstructures after the recrystallization heat treatment at each condition have changed to ferrite–bainite duplex microstructures with fine grains of only several tens of micrometers, appearing nearly the same as unused base material.

In the untreated material, creep cavities are seen to be present at the grain boundaries and subgrain boundaries. In contrast, while the cavities continue to exist along the grain boundaries for case 1, the linked cavities formed during multiple heatings to the $A_3$ transformation temperature are seen to pass through contiguous grains. This indicates that recrystallization heat treatment is effective by separating the cavities from grain boundaries, and that multiple heat cycles around the $A_3$ transformation point are more effective. However, no clear difference was found irrespective of the number of heatings in the case of multiple heat cycles.

From the perspective of the reorganization of the grain boundaries, there may be no necessity for cooling to room temperature after heating, and, considering the time involved in such cooling, case 4 is characterized by shorter processing time. Consequently, case 4 is adopted for the crack propagation, as discussed below.

3.3. Creep Crack Propagation Testing of the Recrystallization Heat Treatment Specimen

Figure 4 presents optical microstructures before and after recrystallization heat treatment of the creep crack propagation test specimen. While the untreated material shows martensite phase microstructures, the recrystallization heat-treated material exhibits a ferrite–bainite duplex microstructure. Also, because the grain boundaries of the treated material were reorganized due to the heat cycles around the $A_3$ transformation point, the cavities are seen to be separated from grain boundaries. As a result, the cavities are rendered harmless. Thus, it is deemed that the recrystallization heat treatment performed on the outer layer using...
the round type coil was well effective. Although the number of cavities was quantified using the number density of creep cavities method, no major change in the number of cavities before and after the recrystallization heat treatment test was detected. This is due to the fact that the objective of the test was not cavity sintering, but rather heating of the entire sample, so that compressive force due to thermal stress was not operative.

Figure 5 presents the results of creep crack propagation test for the recrystallization heat-treated material in comparison with those for the damaged (but untreated) material. It can be seen that the crack propagation rate for the treated material falls to about 1/2 of the untreated material, indicating that the treatment is effective in reducing the propagation rate. Considering the detection of cracks in high temperature reheat piping in an actual boiler, creep crack propagation analysis was carried out based on the acquired test data. The results of this analysis are shown in Fig. 6. Analysis conditions consisted of wall thickness of 31.7 mm, crack height of 6.3 mm, applied stress of 27.5 MPa, and temperature of 814 K. In the case of damaged material on which recrystallization heat treatment was not performed, the crack penetration life is approximately 17,000 h, while data for the treated material suggests crack penetration life of approximately 30,000 h. It is thus confirmed that recrystallization heat treatment serves to extend the creep crack propagation life of damaged material, and is effective for damage recovery.

4. Discussions

4.1. Cavity Sintering Mechanism

Several reports on cavity sintering have been published. Among these, Shinya et al. presented in details the work examining cavity sintering processes for austenitic stainless steel involving isothermal heating and hydrostatic pressure heating as well as heating under uniaxial compressive stress. Isothermal heating was found to sinter a high proportion of small cavities at the initial life stage, but the sintering rate for cavities that had grown to a certain size along the grain boundaries at the middle life stage was extremely slow, countering any expectation that such larger cavities could be effectively sintered by this method. With the hydrostatic pressure heating and uniaxial compressive stress heating techniques, however, the cavity sintering rate was reported to be higher than that for isothermal heating. Shinya et al. also examined the influence of compressive deformation at room temperature, finding that, while cavities tended to be mechanically crushed due to compressive strain at room temperature, this tendency was at a level that could basically be ignored unless there was an exceptionally large amount of deformation. Cavity disappearance was thus controlled mainly by the process of diffusion. Thus, the cavity sintering effect becomes greater as the heating temperature is higher and these results are in agreement with published reports.

Considering the differences among the above-noted isothermal, hydrostatic, and compressive stress heating techniques, a cavity sintering model was presented, as indicated in Fig. 7. This approach applies the constrained growth model for cavities as proposed by Dyson et al. That is, accompanying the movement of atoms from the grain boundary to the cavities surface, strain occurs around cavities and the grain boundary, and this strain acts as a barrier whereby grain boundary diffusion is constrained. Accordingly, mechanical removal of this strain serves as a means of unconstraint grain boundary diffusion. Shinya et al. considered compressive creep deformation as a process that removes the constraint on grain boundary diffusion. Thus, the cavity sintering effect becomes greater as the heating temperature is higher and the compressive strain is larger. The results were a similar tendency to the result by Shinya et al.

As per the foregoing discussion, the application of compressive strain to cavities and neighboring grain boundaries at a high temperature with a high diffusion rate is thought
to be effective in cavity sintering.

4.2. Damage Recovery by Means of Regenerative Heat Treatment

As noted above, it was confirmed that cavities are sintered and disappear when compressive stress is applied at high temperature. Thus, cavities that were created in high energy piping weldments can also be expected to disappear when they are exposed to high temperature and compressive stress. Regenerative heat treatment was thus regarded as a technique to extended the life of weldments.

Figure 8 shows the principle of this regenerative heat treatment process, which takes place in two steps. The first step is creep cavity compression to reduce the number of cavities by applying compressive force while heating to a designated temperature. The next step is recrystallization heat treatment to adjust the microstructure to that of the base material by means of heat treatment at a temperature around the A<sub>3</sub> transformation point. This also separates existing cavities from the grain boundaries.

The mechanical force for the compression treatment of cavities requires very large-scale equipment for high energy piping, which is not realistic due to the required cost and space. Therefore, thermal stress generated by induction heating is employed to apply the required compressive force to the cavities. In induction heating, an induced current is generated in the piping with a magnetic field generated by current flowing in a heating coil.

In order to estimate the compressive stress generated in the material during inductive heating, temperature data was obtained via inductive heating tests with a flat plate, providing the basis for non-steady state FEM temperature stress analysis. Figure 9 shows the state of heating tests using a 50 mm diameter heating coil, and the temperature measurement positions. In conjunction with the measured temperature data during the heating tests, the heat gain and heat input range were selected by means of non-steady state FEM temperature stress analysis. Figure 10 presents a comparison of temperature as measured during heating tests with temperature as obtained from analysis (calculation). These show extremely good agreement, and it was
thereby confirmed that the analysis conditions were appropriate.

Figure 11 shows the non-steady state FEM temperature stress analysis model and an example of the temperature-stress distribution, while Fig. 12 indicates the relationship between calculated temperature and generated stress. The heat input used for analysis was determined from heating test on Fig. 9. Compressive stress increases with temperature elevation, reaching a maximum of 332.4 MPa at 693 K. Here, compressive strain is 0.319%. Subsequently, compressive stress declines due to reduced material rigidity accompanying higher temperature, becoming 9.5 MPa at 1253 K, with compressive strain of 1.04% (the maximum level). Thus, localized high temperature heating becomes possible to give compressive strain to the heating part. However, stress then switches to tension during cooling after the completion of heating, with tensile stress of 451 MPa applying at the termination of cooling. Therefore, measures to decrease residual stress are necessary during cooling process.

5. Conclusions

Technology for the active removal of damage and regeneration for material subjected to creep damage in high energy piping in thermal power plants has been proposed, provided that such recovery is undertaken before the damage reaches the macroscopic stage, and the possibility of life extension for deteriorated material has been considered. This can be summarized as follows:

1. A regenerative heat treatment method using localized inductive heating has been proposed as a means of recovering microscopic damage and extending life with respect to creep damaged high energy piping weldments in thermal boilers.

2. Even in low alloy steel, the application of compressive strain at a high temperature resulted in cavity sintering and a reduction in the amount of formation. The cavity sintering effect becomes greater as the heating temperature is higher and the compressive strain is larger.

3. It was confirmed that heat cycle application around the transformation point serves both to refresh deteriorated weldment microstructure to the one equivalent to the base material, and to promote the separation of cavities from the grain boundaries, rendering them harmless.

4. Regenerative heat treatment performed on a test specimen reduced the creep crack propagation rate to approximately 1/2 of that of untreated material. Accordingly, it was confirmed that the application of this regenerative heat treatment is effective in life recovery of deteriorated weldments.

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