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SP creep properties of Gr.91 boiler pipings service-exposed in different USC power plants

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Abstract: The small punch (SP) testing technique was applied to five heats of Gr.91 steel, which had been actually used for boiler pipings in different USC power plants for long periods of time to investigate the applicability of this technique to the assessment of heat-to-heat variation of creep property. The experimental results revealed that the SP creep rupture strength and deformation behavior were quite different depending on the heat. Those differences in SP creep property, which could not be evaluated by hardness measurement, were qualitatively similar to those in standard uniaxial creep one. It was expected that the SP creep testing technique was applicable to the assessment of heat-to-heat variation for in-service boiler pipings.

Keywords: small punch creep test; USC power plant; boiler pipings; heat-to-heat variation; Gr.91 steel

1. Introduction

9-12%Cr heat resistant ferritic steels, such as Gr.91, Gr.92 and Gr.122 steels, have been widely used in ultra-super critical (USC) power plants, because of their superior high temperature strength and resistance to corrosion/oxidation. But, premature failures at their welded joint have been a worldwide issue in recent years. This failure occurs at the outer edge of the heat affected zone (HAZ), and it is well known as “Type IV creep damage”. It has been recently revealed by the co-author that the creep strength of welded joint is closely associated with that of base metal. That is to say, when the base metal has an insufficient strength, the strength of its welded joint is also low leading to unexpected premature failure. Figure 1 [1] shows the comparison of creep rupture lives of two different heats of Gr.91 steel (base metal and welded joint), which had been actually used for a long period of time in USC plants A and B. As can be clearly seen in this figure, the Gr.91 steel of B plant has much lower creep rupture strength than that of A plant for both of base metal and welded joint. The creep rupture life of welded joint removed from B plant is only a fifth of that removed from A plant, and the difference is more pronounced for the base metal. This result indicates that it is very important to assess variation in creep strength of in-service pipings, i.e., heat-to-heat variation, and the creep strength of welded joint may be roughly estimated if that of base metal is available.

In the late 1970s and early 1980s, the small punch (SP) testing technique using a miniaturized disk-type specimen was developed for determining post-irradiation mechanical properties. This technique has been widely used for evaluating various material properties, such as tensile property, ductile-brittle transition behavior, fracture

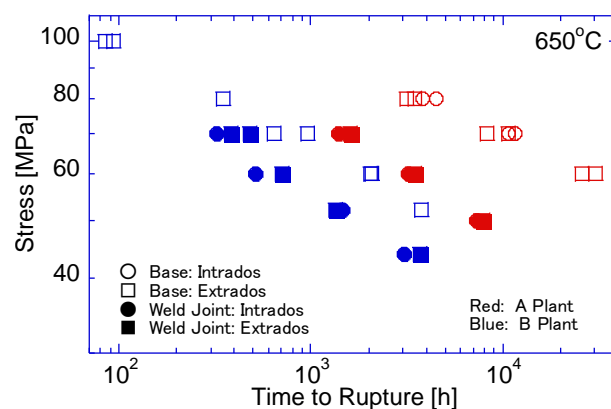


Figure 1. Comparison of creep test data of long-term used Gr.91 steels [1].

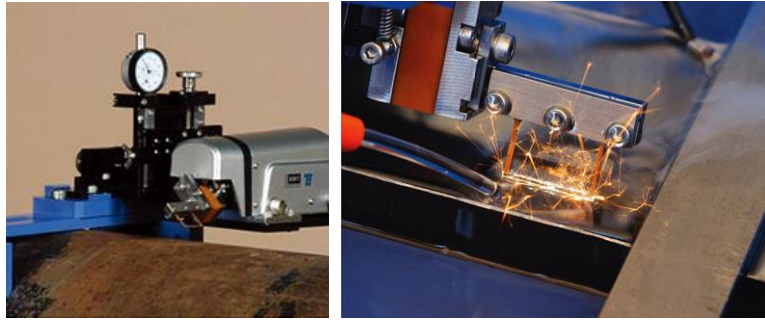


Figure 2. On-site electric discharge sampling equipment with copying mechanism.

toughness, hydrogen embrittlement, and stress corrosion cracking. It has also been successfully employed in evaluating high temperature creep property. Since this SP creep test requires only a small amount of sample, the damage caused by removing the sample from components can be minimized. In recent years, a novel on-site electric discharge sampling equipment with copying mechanism has been also developed for this purpose (Figure 2 [2]). This equipment is capable of taking a small plate-type sample as thin as 1 mm from the component's surface.

In this study, the creep property of Gr.91 steel was measured by the SP testing technique for investigating the applicability of this technique to the assessment of heat-to-heat variation of creep strength. The SP creep test was carried out at the temperature of 650°C and under the loads of 190, 230, 300 N using the Gr.91 steel base metals removed from five different boiler pipings, which had been actually used in the USC power plants for a long period of time.

2. Materials and Experimental Procedures

Table 1. Nominal dimensions and operating conditions of Gr.91 boiler pipings.

	Nominal dimensions	Operating conditions
Plant A	Elbow pipe (Plate) $\phi 711 \times t39$ mm	Temp.: 593~608 °C Pressure: 3.9~4.7 MPa Time: 54000~142000 h
Plant B	Elbow pipe (Plate) $\phi 457 \times t22$ mm	
Plant M	Straight pipe (Plate) $\phi 864 \times t43$ mm	
Plant N	Elbow pipe (Plate) $\phi 610 \times t29$ mm	
Plant T	Straight pipe (Plate) $\phi 864 \times t51$ mm	

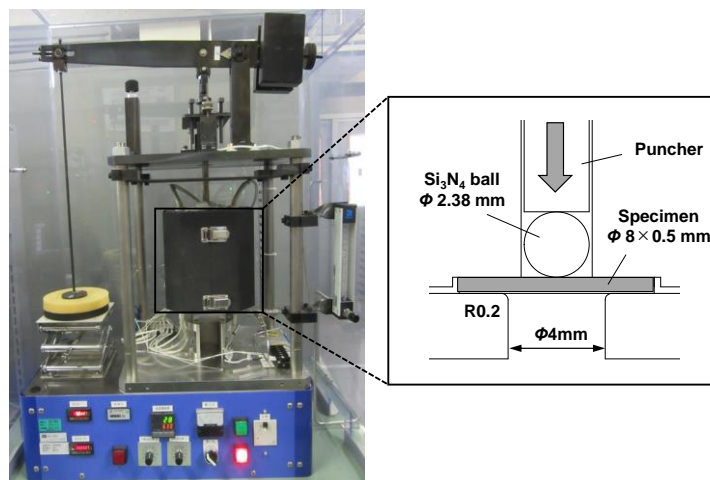


Figure 3. SP creep test apparatus and loading and specimen support configuration for SP creep test.

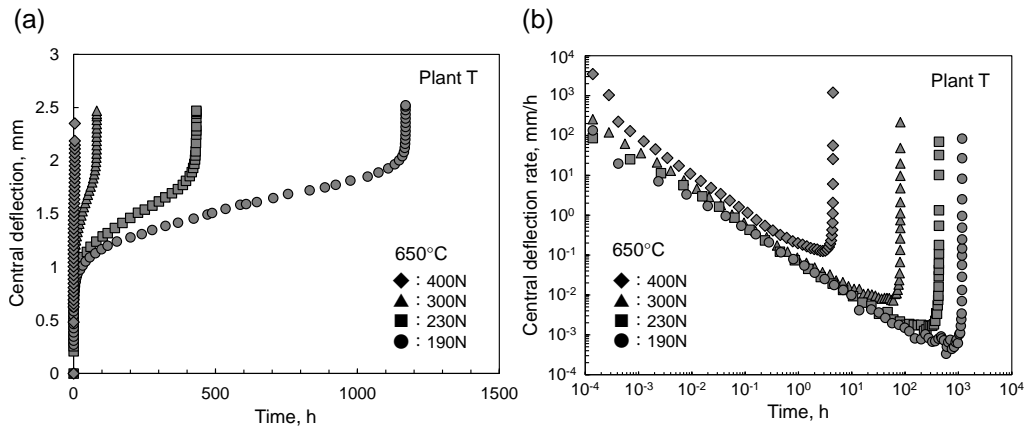


Figure 4. SP creep test results obtained from heat N: (a) Time-central deflection curve; (b) Time-central deflection rate curve.

The materials used in this study were five different heats of Gr.91 steel (base metal), which had been actually used for boiler piping in different USC power plants (plants A, B, M, N, T) for a long period of time. Their nominal dimensions and operating conditions are summarized in Table 1. There was almost no difference in hardness between them in spite of significant difference in creep property.

The small disk-type specimen (8 mm in diameter) was prepared for the SP creep test. Both sides of the specimen were carefully ground to a thickness of 0.5 mm with a thickness tolerance of 0.005 mm. The specimen surfaces were finally polished using 0.3 μm Al_2O_3 solution. As schematically illustrated in Figure 3, the specimen was tightly clamped between the upper and lower dies, and a certain constant load was applied on the center of specimen through a puncher and Si_3N_4 ball (2.38 mm in diameter). The central deflection was continuously measured by recording the displacement of compression rod using a linear variable differential transformer (LVDT). The SP creep test was carried out at the temperature of 650°C and under the loads of 190, 230, 300, 400 N. In order to avoid severe oxidation of the specimen, the test was performed in an argon gas atmosphere and the gas was continuously passed through during the test.

3. Results and Discussion

As examples of SP creep test result, the time-central deflection curves and the time-central deflection rate curves measured on the heat T (Gr.91 steel taken from the plant T) are given in Figure 4. As reported in the previous studies [3-5], the overall shape of curve is qualitatively similar to that obtained from standard uniaxial creep test, although the instantaneous deflection is significant at the time of initial load application in the SP creep test (Figure 4 (a)). This enormous deflection is attributable to the plastic bending deformation rather than the creep one. After the initial load application, the specimen experiences an instantaneous high stress due to small initial contact area

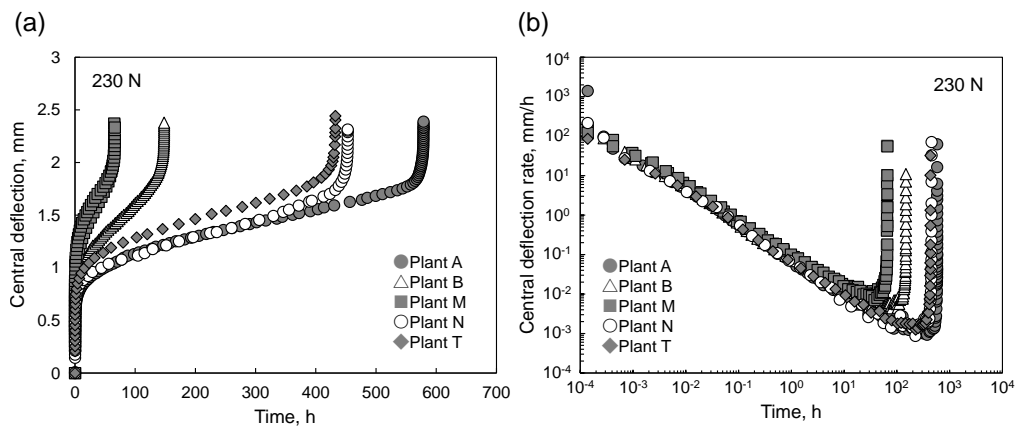


Figure 5. SP creep test results of heats A, B, M, N and T: (a) Time-central deflection curve; (b) Time-central deflection rate curve.

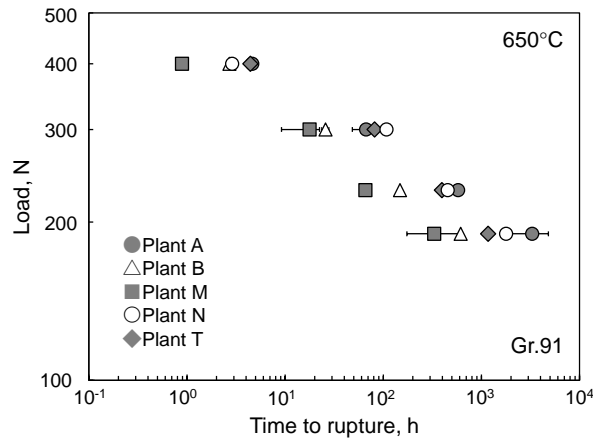


Figure 6. SP creep rupture test results of heats A, B, M, N and T.

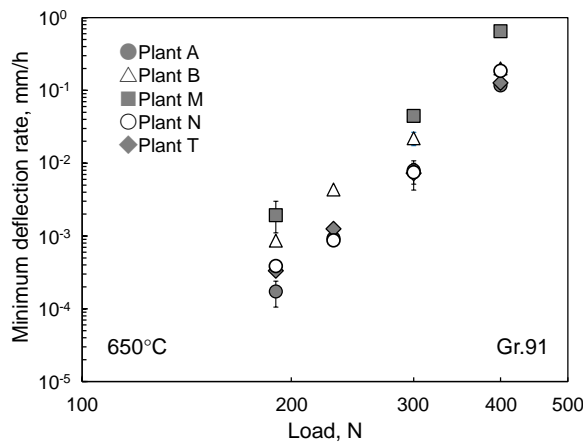


Figure 7. Minimum deflection rate measured on heats A, B, M, N and T.

between the specimen and ball. This high stress causes higher plastic deformation and thereby large bending deflection. It can be seen from the time-central deflection rate curves (Figure 4 (b)) that the deflection rate in the transient region shows no difference irrespective of test condition. This result means that the SP creep proceeds under similar deformation mechanism. However, the minimum deflection rate decreases with decreasing applied load, resulting in longer time to rupture. There is no significant difference in the central deflection to rupture, and it is around 2.5 mm irrespective of test conditions.

Figure 5 shows the time-central deflection curves and the time-central deflection rate curves of five heats measured at 650°C/230 N. As can be clearly seen, the rupture life is obviously different depending on the heat. The rupture lives of heats A and M were 579 and 65 h respectively, and the former was almost ten times as long as the latter. The rupture life of heat B is also relatively short compared with the heats A, N and T. Figure 6 shows the results of SP creep rupture tests, where the time to rupture is plotted against the applied load. The rupture lives of heats A, N and T are as a whole longer than those of heats B and M, and this difference seems to be more pronounced with decreasing applied load although some scattering results can be seen. At the lowest applied load of 190 N, the time to rupture of heat B is almost one order of magnitude shorter than that of heat A. The minimum deflection rate measured by the SP creep test is plotted against the applied load in Figure 7. The minimum deflection rate is different depending on heat, and, according to the time to rupture, the rate is also decreased in approximately the following ascending order: heats A, N, T, B and M. Figure 8 shows the relationship between the minimum deflection rate and the time to rupture. There is a unique correlation between those quantities irrespective of heats and test conditions, which is well known as Monkman-Grant correlation in uniaxial creep.

Figure 9 shows the SEM micrographs of specimens ruptured at 650°C/230 N. In all the specimens, the fracture occurred at a distance away from the center of specimen along the circumference, where the stress and strain had

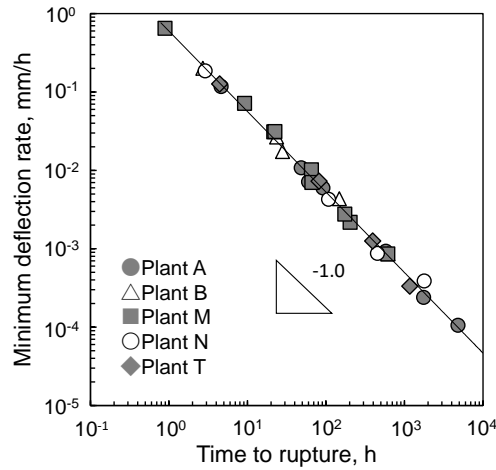


Figure 8. Relationship between minimum deflection rate and time to rupture.

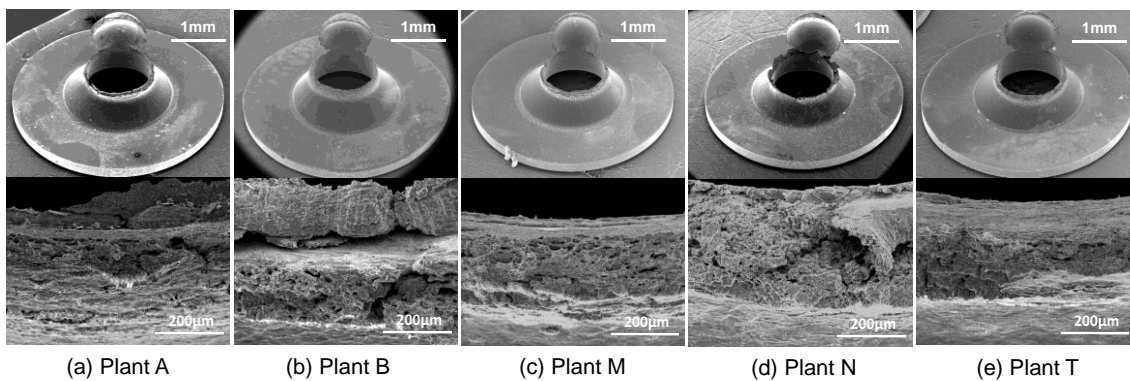


Figure 9. SEM micrographs of SP creep specimens ruptured at 650°C/230 N.

maximum values. A cap-like part remained on the specimen without dropping out even after complete fracture. This macroscopic fracture morphology is a typical characteristic of ductile materials. No brittle fracture surface like an intergranular cracking was observed in all of the heats under the present test conditions. The fracture modes of all the specimens were a typical ductile transgranular with dimples, and there was no large difference in fracture irrespective of the steels and test conditions.

Those differences in SP creep strength and deformation properties between the five different heats are qualitatively similar to those in standard uniaxial creep ones [1, 6]. The results obtained in this study indicated that the SP creep testing technique was applicable to the assessment of heat-to-heat variation of creep property for in-service boiler pipings.

4. Summary

The small punch (SP) testing technique was applied to five heats of Gr.91 steel, which had been actually used for boiler pipings in different USC power plants (A, B, M, N, T) for long periods of time, to investigate the applicability of this technique to the assessment of heat-to-heat variation of creep property. The experimental results revealed that the SP creep rupture lives of heats A, N and T as a whole were longer than those of heats B and M. Additionally, according to the creep rupture strength, the minimum deformation rates were also decreased in approximately the following ascending order: heats A, N, T, B and M. Those differences in creep property, i.e., heat-to-heat variation were also measured by the standard uniaxial creep test, and there was a qualitatively good correlation between the results of SP and uniaxial tests. The results obtained in this study indicated that the SP creep testing technique was a strong tool for the assessment of heat-to-heat variation of creep property for in-service boiler pipings.

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