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# Miniature creep tests using plate specimens bonded by electron beam welding

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**Abstract:** Many aged thermal power plants restarted to supply sufficient electricity for Japanese industries and daily activities after the seismic earthquake. Reasonable guidelines for assessment of their integrity and estimation of remaining life have been required to operate them with a safety margin. Miniature Creep (MC) test is recognized as a semi-destructive technique to examine the degradation level of aged high temperature components. The MC thin plate specimen of 2.25Cr-1Mo steel and the similar one welded by Electron Beam (EB) for gauge length were employed to evaluate the validity of the EB welded MC thin plate specimen. A series of creep tests using the MC thin plate specimens were conducted in vacuum at 600°C. Then, following conclusions were obtained: (1) Creep rupture lives of the MC thin plate specimens welded by the EB were nearly the same as those of standard ones. (2) Vickers' hardness in the welded zone decreased in a short time after the test started and reached almost the same as or below that in the base metal. (3) Rupture lives of the EB welded MC thin plate specimen at higher stress levels were longer than those of the standard MC thin plate specimen.

**Keywords:** Miniature Creep Test; Electric Beam Welding; Miniature Thin Plate Specimen; Vickers' Hardness; Residual Creep Life

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## 1. Introduction

Great East-Japan earthquake which magnitude was 9.0 happened on March in 2011. Within only an hour, a giant Tsunami generated by the earthquake hit the Japan's east coast. The maximum height of tsunami was about 20 meter, which was much higher than ever expected. Many atomic power plants were located along east coastline of the main island of Japan. Three of them were severely damaged, because they lost cooling systems that were installed under the ground. Unfortunately, two atomic power plants caused meltdown/melt-through due to overheat of the main reactor. After the disaster, all atomic power plants in Japan had completely stopped the generation of electricity for several years. About 30 % of total electricity in Japan were supplied by the nuclear plants at that time. However, a certain amount of electricity has been required to maintain daily lives and industrial activities using other alternative means, even if the atomic power plants stopped. There were many suspended fossil power plants, but some of them were not able to perform the full performance because they were a bit old and not always guaranteed to operate safely. Then, some reasonable guidelines were required to generate the electricity using these old fossil power plants.

There are two main methodologies to evaluate the integrity of high temperature power plants, *i.e.*, destructive test and non-destructive test (NDT). Although the destructive test shows higher reliability comparing with the NDT, it has some drawbacks; much more labor and time are taken to conduct these tests. Furthermore, specimens in the destructive test usually require a relatively large volume to sample from actual components. However, sampling large volume specimens sometimes damage target components, and it is also difficult to collect the standard uniaxial specimen from thin plates or grooves/edges with sharp angles. Furthermore, examined components would not be able to reuse even if its integrity was guaranteed after the inspection. Thus, another new testing method using a smaller volume of specimen has been required. Small Punch Creep (SPC) test has been recently proposed to fit these requirements, and their test results have been proved profitable [1-4]. However, the SPC test has an inevitable issue; how to convert test load in the SPC test to stress in the uniaxial creep test? Some significant interpretations and/or useful transformations have been proposed [5-6].

In order to avoid this issue, a miniature creep (MC) test has also been proposed as one of the semi-destructive tests [7-8], where the uniaxial stress can be employed as an index. Since the uniaxial stress as a parameter is the

same as that in the standard creep test, uniaxial creep test data accumulated so far will be widely utilized to evaluate the integrity of aged components. Although the volume of specimen for the MC test is smaller than that of the standard uniaxial one, much less volume specimen should be introduced to examine restricted zones in the components. If only limited zones can be employed as a gauge length (GL) in the MC specimen, the volume for inspection could be greatly reduced. In this paper, an electron beam (EB) welding method was introduced to bond the GL with grip ends using the same material. A series of creep tests were performed employing two standard uniaxial round bar, the standard MC thin plate and the EB welded MC thin plate specimens. Then, it was shown that creep rupture lives of the MC specimens with the EB welding were nearly the same as those of the standard round bar and the standard MC thin plate specimens.

## 2. Materials and Testing Methods

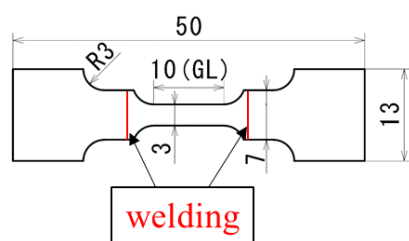
### 2.1. Test Material and Specimens

A low alloy heat-resistant steel, SCM4V termed as 2.25Cr-1Mo steel in general, was employed here. It is a rolled thick plate with a thickness of 32 mm, 163 mm wide, and 233 mm long. Vickers' hardness test was performed on each section of the material; longitudinal rolling direction and two transverse sections. Then, it was shown that the hardness was independent on each section. The grain size number of the test material was #8 to #9.

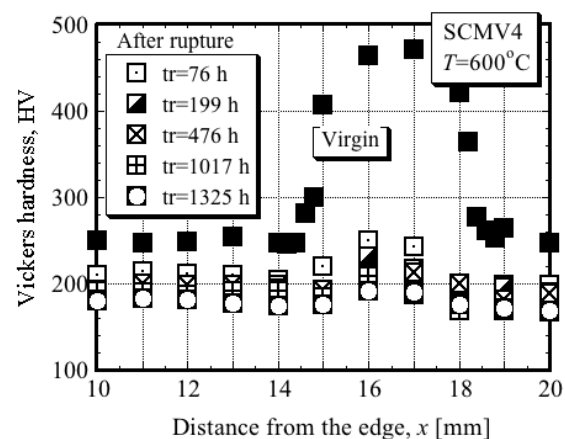
Tensile axes of all specimens were cut along the rolling direction of the thick test plate. Two standard round bar specimens were employed, which have diameters of 8 mm and 5 mm, and these corresponding gauge lengths were 38 mm and 20 mm each. These specimens were machined from a usual lathe processing.

Configuration and dimensions of the standard MC and the EB welded MC thin plate specimens are illustrated in Figure 1. The EB welded MC thin plate specimens were welded using three subdivided plates, and then cut to the prescribed shape using an electric discharge machine. Two red lines shown in Figure 1 indicate the EB welded parts. The normal standard MC plate specimen requires at least the area of 50 mm x 13 mm. On the other hand, the area for the EB welded MC plate specimen can be reduced to 15 mm x 7 mm, and then its area ratio is nearly below a sixth. Thickness of each MC thin plate specimens is 1.00 mm. Both surfaces of the MC thin plate specimens were carefully polished with the emery paper of up to # 2000 fine grit before the tests.

Figure 2 show distributions of Vickers' hardness along the loading axis in the vicinity of the EB welding joints. In the horizontal axis, the area indicated from  $x = 14.5$  mm to 18.5 mm is the welded zone and the GL is located in over  $x = 18.5$  mm. Initial distributions of Vickers' hardness are depicted as the solid squares. Width affected by the EB welding is about 4 mm, and its hardness is twice harder than that of the base metal. The hardness of exposed area in an electric furnace including the GL is almost the same as that of the base metal.



**Figure 1.** Configuration and dimensions of Miniature Creep (MC) thin plate specimen. Red lines show the zones welded by Electric Beam (EB), and the thickness of the specimen is 1 mm.



**Figure 2.** Distributions of Vickers' hardness on MC thin plate specimen around the EB weld lines. Solid squares were measured before the test, and other open symbols show the values measured after the creep tests.

## 2.2. Testing Apparatus and Procedures

Uniaxial creep tests using the round bar specimen were performed in air with a standard single lever creep machine. Test temperature was set to 600°C. The creep machine for the MC thin plate specimens were newly developed and shown in Figure 2 (a). Here, an enlarging load lever system was not adopted in this machine, because the testing load was very small, so the load was directly applied to the specimen. In order to avoid oxidation of the MC thin plate specimens, this machine equips with a vacuum chamber. The specimens are set up inside this chamber that provided  $2 \times 10^{-4}$  Pa vacuum degree (Figure 2 (b)). An extra guide rod was inserted between the upper and the lower grip ends to prevent bending the specimen during the tests.

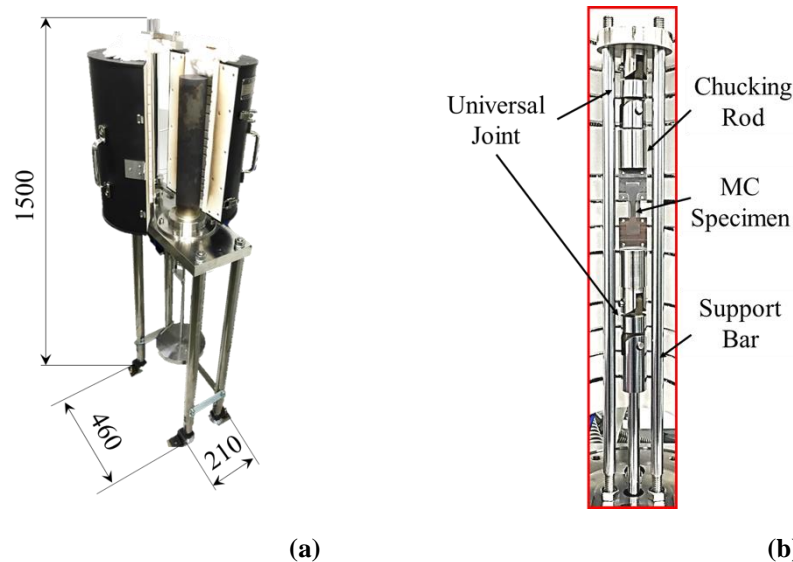
If the thermocouple for controlling the test temperature were welded on the MC thin plate specimen, welded spots would have been damaged, and the rupture life would have been shortened. Thus, a difference of temperature between the MC thin plate specimen and a fixed spot inside the chamber was measured in advance, and the temperature at the fixed spot was always controlled through the tests.

All the creep tests were started after 12 hours later when the temperature of the specimen reached 600°C. Displacement of the loading rod was monitored with a linear gauge to measure the deformation between the grip ends and recorded on a chart recorder till rupture. Since the total deformation in the MC thin plate specimen includes rounded zones besides the GL, the deformation of GL was distinguished from the total one using the FE analysis. Thus, the creep strain and its rate in the MC tests were calculated. The actual equation, the theta projection, employed in the analyses is expressed as follows;

$$\varepsilon = \theta_1 \{1 - \exp(-\theta_2 t)\} + \theta_3 \{1 - \exp(-\theta_4 t)\} \quad (1)$$

$$\theta_1 = 7 \times 10^{-8} \sigma^{2.46}, \theta_2 = 3 \times 10^{-20} \sigma^{8.20}, \theta_3 = 5 \times 10^{-8} \sigma^{2.60}, \theta_4 = 4 \times 10^{-21} \sigma^{8.51}$$

( $\varepsilon$ : mm/mm,  $t$ : hour,  $\sigma$ : MPa)



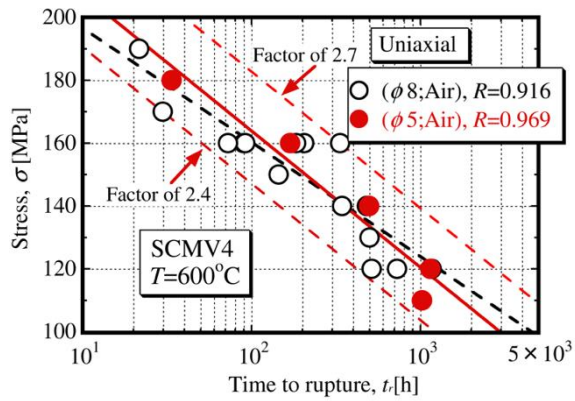
**Figure 3.** Creep machine newly developed for the Miniature Creep (MC) test. (a) Total view of the testing machine; (b) Set-up of the MC thin plate specimen inside the vacuum chamber.

## 3. Creep Test Results and Discussions

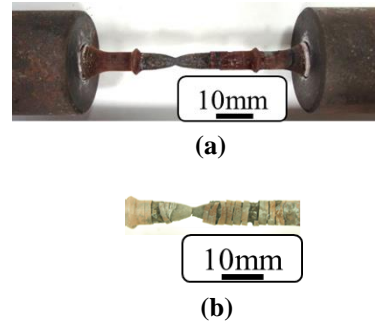
### 3.1. Results of the round bar specimens

Figure 4 shows creep test results employing the round bar specimens of 5 mm and 8 mm in diameter. Two solid lines are drawn using a least-square method. In this figure,  $R$  denotes a correlation factor. It seems that there is a bit larger variation on rupture lives in the tests of 8 mm round bar specimen, shown as the open circles. This may be caused by the fact that these specimens were sampled from different individual plates.

Figures 5 (a) and (b) show appearances of 5 mm round bar specimen at rupture. These creep tests were conducted in air, so some oxide films were formed on the surface of specimens. Especially, severe ring-type oxide



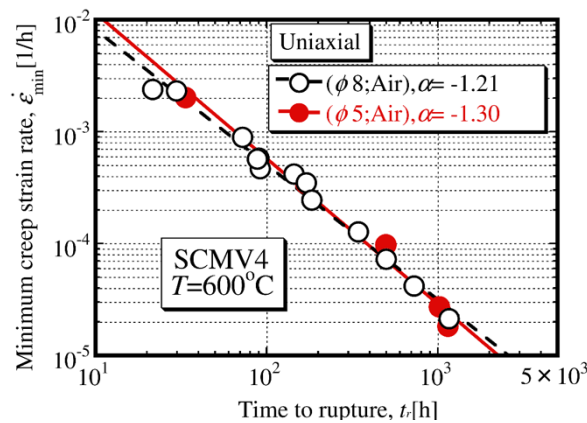
**Figure 4.** Relationship between the applied stress and time to rupture using round bar uniaxial specimens. All tests were performed in air.



**Figure 5.** Appearance of ruptured round bar specimens of 5 mm in initial diameter.

(a) Stress is 120 MPa,  $t_r = 1,146$  hours;

(b) Stress is 110 MPa,  $t_r = 1,022$  hours.



**Figure 6.** Monkman-Grant relation in the creep test employing the round bar specimens. Each solid line is drawn by using the least-square method.

films were found on the specimen tested at the stress of 110 MPa (Figures 5 (b)) due to long exposure. These thick oxide films reduced the diameter of round specimens, and then the actual stress on the net section was increased; the rupture life at 110 MPa was a little shorter than the statistically predicted solid red line.

Monkman-Grant relationships are shown on Figure 6. Slope  $\alpha$  in this relation is a bit steeper comparing with other literatures [9]. However, there was little dependency on whichever the specimen was employed.

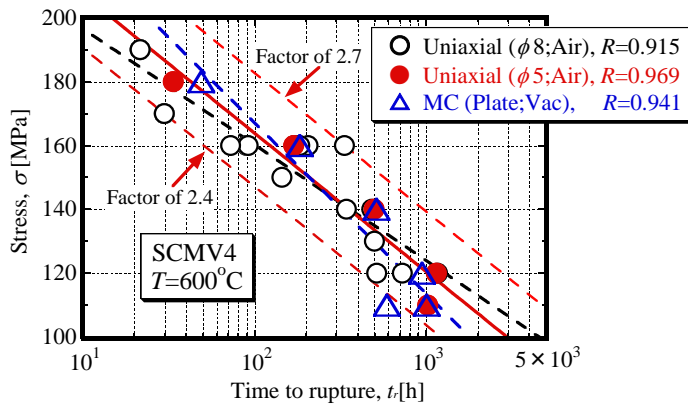
### 3.2. Results of the MC thin plate specimens

In this section, the creep test results using the MC thin plate specimens were shown and discussed dividing into two items; (1) standard MC thin plate and (2) EB welded MC thin plate specimens.

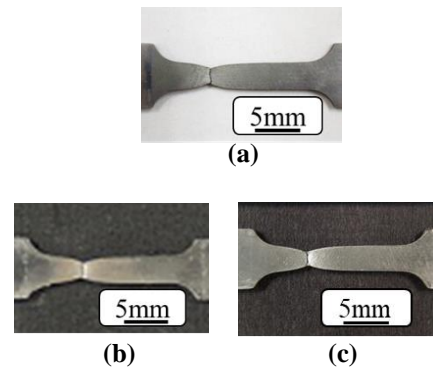
#### 3.2.1. Case #1; Standard MC Thin Plate Specimen

Creep curves employing the standard MC thin plate specimens exhibited nearly the same manner as the those of the round bar specimens; the primary stage of creep rarely appears, the secondary and the tertiary stages of creep occupies most of creep life.

Creep rupture data employing the standard MC thin plate specimen are plotted in Figure 7 as blue open triangles. The MC thin plate specimen at higher stress levels has a tendency to extend its rupture time a little longer than that of the round bar specimens, but the lifetime at lower stress levels sometimes become to be shortened. Especially one specimen at the stress of 110 MPa broke in a very short time. Although the reason why this causes has currently been unclear so far, rupture lives of the round bar specimens at lower stress levels are also shorter than the solid red least-square line derived from the test results using MC thin plate specimens.



**Figure 7.** Relationship between the applied stress and time to rupture for the standard MC thin plate specimens.



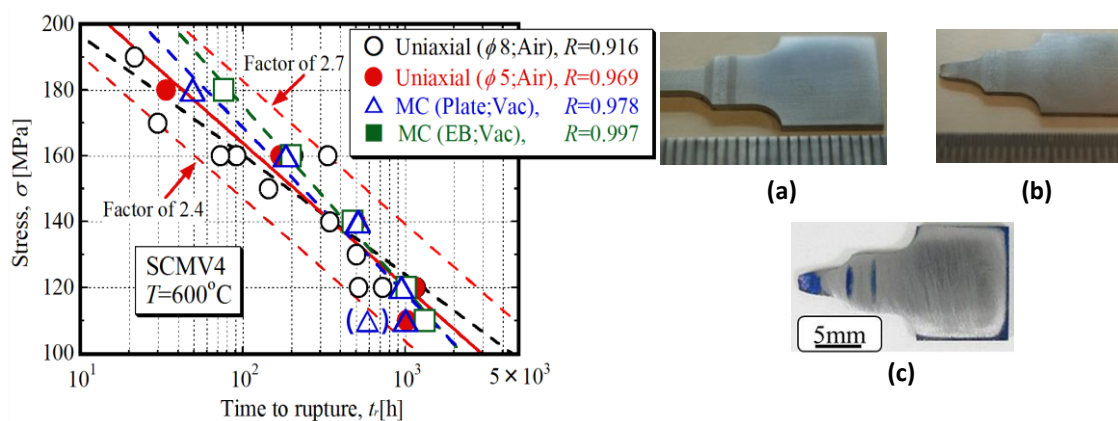
**Figure 8.** Appearance of standard MC thin plate specimens at rupture.

- (a) Stress is 120 MPa,  $t_r = 970$  hours;
- (b) Stress is 110 MPa,  $t_r = 1,006$  hours;
- (c) Stress is 110 MPa,  $t_r = 591$  hours.

Figures 8 (a) to (c) show appearances of the standard MC thin plate specimens at rupture. These tests were conducted in vacuum. Little oxide film was observed on the surface of specimens, and superficially there was little differences between the specimens at the stress of 110 MPa even if the rupture time was significantly different (Figures 8 (b) and (c)). In order to calculate the creep strain and its rate on the GL of the MC thin plate specimen, the theta projection was applied in the FE analysis, where the creep data obtained in Section 3.1 were employed [10].

### 3.2.2. Case #2; EB Welded MC Thin Plate Specimen

Relations between the rupture time and the applied stress for the EB welded MC thin plate specimens are added in Figure 7, and they are displayed as green open squares in Figure 9. Their rupture lives are plotted near those using the standard MC thin plate specimens or a little longer than them, and variations fall within nearly a factor of two based on the solid red line. This relation may be caused by the reason why the welded zone had higher strength than the base metal. Figure 2 demonstrates that Vickers' hardness around the welded zone decreases in a short time soon after the test starts, and the welded zone gradually softens with time. In Figure 9 a test result at the stress of 110 MPa using the MC thin plate specimen depicted in brackets is excluded to recalculate the least square line, because its rupture time was extremely short.



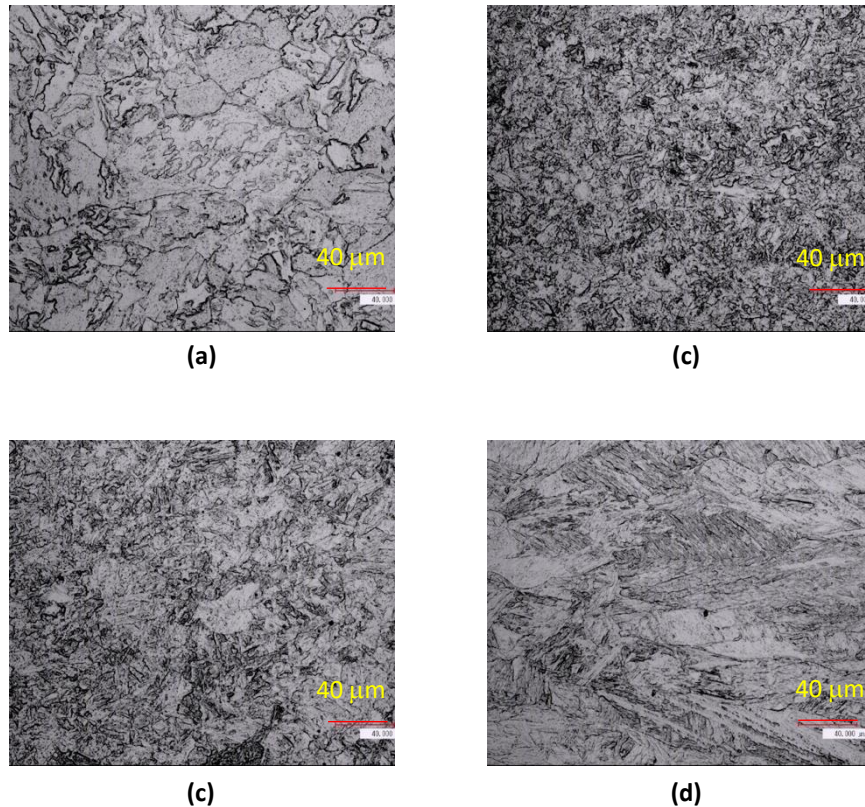
**Figure 9.** Relationship between the applied stress and time to rupture for MC thin plate specimens.

**Figure 10.** Appearances of the welded MC thin plate specimens around the welded zone.

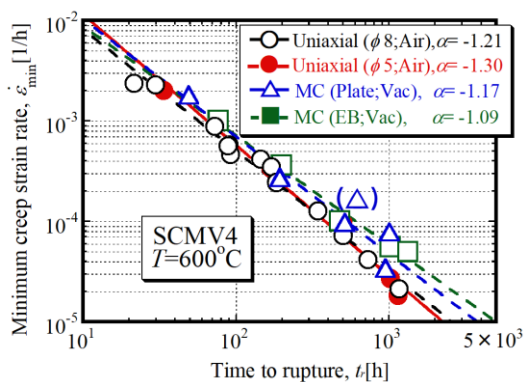
- (a) Before the creep test, (b) After the test,  $t_r = 76$  hours, (c) Dents along HAZ after the test.



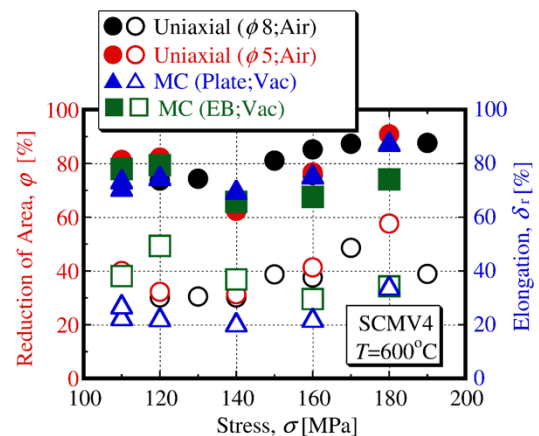
A general view before the test around the welded zone in the EB welded MC thin plate specimen is shown in Figure 10 (a), where two lines in the HAZ can be distinguished clearly. Figure 10 (b) is another photo of the same specimen at rupture. It seems that the two lines disappeared at first glance. After coloring in blue on the surface with an oily marker ink, the specimen was polished and wiped. Dents along the HAZ remain in blue colored in Figure 10 (c). Since the HAZ area was a bit softer than the other ones, it might deform unexpectedly during the creep test.



**Figure 11.** Microstructures in the EB welded MC thin plate specimen. (a) Base Metal; (b) FGHAZ; (c) CGHAZ; (d) Weld Metal.



**Figure 12.** Monkman-Grant relations obtained in this study employing round bar and MC thin plate specimens. Each line is drawn using the least-square method.



**Figure 13.** Relationship between elongation / reduction of area (RA) and applied stress. Open symbols show the elongation, and solid ones RA.

Microstructures of the EB welded specimen before the test are shown in Figures 11. They are (a) Base Metal, (b) Fine Grain HAZ, (c) Coarse Grain HAZ, and (d) Weld Metal. Here, the contents of a corrosion liquid are; 250 mL of Ethanol, 0.9 g of Picric acid, and 1 mL of Nitric acid. It can be seen that each zone has different structures. Every fracture surface of the specimens at rupture was also examined with a laser microscope, and it was found that

dimple patterns covered all fracture surfaces. The diameter of dimples generally depended on the time to rupture: the longer the rupture time, the larger the diameter of dimple was.

All Monkman-Grant relationships acquired here are illustrated in Figure 12. Each dashed and solid lines are drawn using the least-square method. This picture indicates that the slopes in blue and green dashed lines based on the MC plate specimens exhibit a little gentler than those employing the round bar ones. In Figure 9 there is a difference in the creep rupture time at higher stress levels, but in Figure 12, apparent contrast in the minimum creep strain rate can be found at longer rupture lives / in the lower stress levels. This may be caused by conversion results of creep strain in the MC plate specimens. In these creep tests, only the creep deformation between both grip ends of the specimen was measured. In order to calculate the creep strain in the MC plate specimens, the creep deformation of GL must be separated from that of grip ends. Thus, the deformation ratio of the GL to the total one was introduced. FEA results explain that this ratio gradually increases with time; it starts from 0.60, 0.85 at  $t/t_r=0.2$ , and 0.93 at  $t/t_r=0.8$ . However, the creep deformation of the GL in the MC plate specimen at lower stress levels may be calculated a little greater than the actual deformation, because the creep data below the stress of 120MPa were not employed in the FEA due to a lack of those creep data.

Figure 13 displays changes of elongation and reduction of area (RA) with the applied stress, where the elongation depicted as open symbols, and the RA as solid ones. As the results of examining precisely, each index may depend on the type of specimens. However, from a broad viewpoint it seems that both values a bit decrease with the decrease of stress similarly, and round bar specimens indicate a little more ductile failure comparing with the plate specimens. Thus, creep properties, *i.e.*, rupture time and ductility of the EB welded MC thin plate specimens, show nearly the same as those of the standard MC thin plate ones and/or the round bar specimens.

Then, if a very small volume were sampled from target components, its creep properties could be estimated employing the EB welded MC thin plate specimen. Henceforth, it would be studied whether this methodology could be suitable to examine the residual life of aged components or other heat-resistant materials.

#### 4. Conclusions

In order to minimize the uniaxial creep specimen, Individual three parts, *i.e.*, parallel gauge length and grip ends in the plate specimen, were bonded using the electron beam (EB) welding method. The target area can be limited, and then the volume of EB welded MC thin plate specimen can be reduced below a sixth comparing with the standard MC one. In addition to the standard MC thin plate and the standard round bar specimens, a series of creep tests were conducted to examine the validity of EB welded MC thin plate specimen. Then, following results were obtained.

- (1) Creep rupture lives of the EB welded MC thin plate specimens were nearly the same as those of the standard MC thin plate specimens and the round bar ones.
- (2) Vickers' hardness in the welded zone decreased in a short time after the test started, and reached almost the same as or below that in the base metal.
- (3) Rupture lives of the EB welded MC thin plate specimen at higher stress levels were longer than that of the standard MC thin plate specimen.

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