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Original Paper

Low Ductility Fracture at 800K in 2¼Cr-1Mo Steel Welds

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Abstract

The grain boundary fracture was investigated for the simulated weld HAZ with the various size of austenite grain. Two methods of cracking tests were employed; the constant load and the constant extensional rate of the specimen. The former was the ordinary creep rupture test, and the later has been newly proposed in order to simulate the phenomena of fracture along the prior-austenite grain boundary. The grain size affects the crack-initiating time and the fracture mode. The grain boundary fracture was observed at two different extensional rates, that is, about 20 and 0.02 nm/s. The cracking test with the constant extensional rate was useful to examine the grain boundary embrittling during reheating.

Key words

Grain boundary fracture, Creep rupture testing, Austenite grain size, Strain rate, Heat-affected-Zone, Deformation of grain boundary

1. Introduction

The grain boundary cracking is one of serious problems occurring in the heat affected zone of steel welds. Typical examples are known as the reheat cracking[1], the underclad cracking[2], the low ductility creep fracture[3] and some types of temper embrittlement[4]. There are several common natures as followings. 1) The crack propagates along prior-austenite grain boundaries in the coarse-grained HAZ. 2) The crack occurs when the weldment is reheated after the welding to the temperature of about 800 K. 3) The crack occurs in the weldment of the steels containing chromium and molybdenum, and does not occur in the weldment of the mild steel.

These cracks seem to be similar from the view points of appearance of fracture surfaces. However, there is significant difference in the situation of occurring cracks. An underclad crack occurs in HAZ, when the HAZ is reheated by a subsequent bead during multi puss welding. In this case, crack initiates in the very short time range. The reheat cracking, which is originally termed as the stress relief cracking, occurs in the time range of 3 to 30 hours, during heat treatment of stress relief annealing. The low ductility creep fracture occurs in the time range of 1000 to 10000 hours in actual welded constructions. Furthermore, some types of temper embrittlement are reported they occur in the very wide time range of 1 to 10000 hours. These phenomena are identified respectively, because of the difference in crack–initiating time. However, all of these crackings are connected to the weakening the grain boundaries at the elevated temperature.

Many test methods were employed for the investigations of grain boundary cracking. The reheat cracking tests have been carried out by reheating a model specimen of actual weld joint[5]. The modified implant test was also employed in order to examine the stress change during the reheating. Because the strain, which is the total of elastic and plastic strains, is kept constant, the stress applying to the specimen has been decreasing during the test. That is, the specimen would be fractured with stress relaxation. This testing condition will be closely similar to that of the actual weldment. However, it is difficult to determine the effect of the stress on the crack–initiating time by these testing method[6]. Creep rupture tests are performed with the constant load, or the constant stress on the assumption that the crosssectional area of the specimen is constant. In the case of constant load test, the effect of stress is clearly defined, however, the deforming rate of the specimen will be larger than that of actual weldment, especially at the end of cracking test. If the strain rate is one of the factors affecting the occurrence of grain boundary crack, the constant loading test will be unfavorable to investigate the cracking phenomena.

The new cracking test method was employed in this paper to investigate the influence of the strain rate on the occurrence of grain boundary crack. The loading device controls for the extensional rate of the specimen to keep constant during the test. The condition of this method will differ to actual weldment, however, it will be useful for obtaining the fundamental information about the grain boundary fracture.

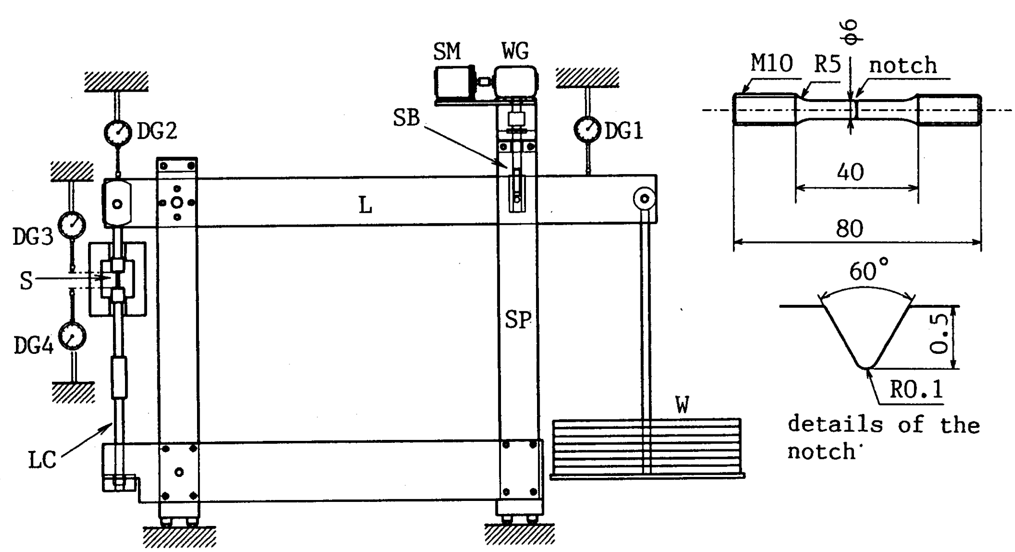

Fig.1 The apparatus for the cracking test and the dimrnsions of the specimen

2. Experimental procedures

2.1 Testing machine

Fig.1 shows the testing machine used in the present paper. This machine was for the ordinary creep rupture test with constant load[7]. The weight (W) supplies the tensile stress in a specimen (S), which is multiplied by the factor of 7 using the lever (L). This machine can be used for the creep rupture test, taking off the controlling device mentioned below.

The lever of the machine was equipped with the controlling device to the deforming rate of specimens. The lever is lifted by the screw bolt (SV) , which is fitted to the support pillar (SP). Therefore, all of the dead load of the weight does not act directly to the specimen, and the applying load to the specimen is the difference between the dead load of the weight and the force applying the screw bolt. The load applied to the specimen is measured by the load cell (LC). The screw bolt was revolved very slowly by the woam gear (WG) driven by the stepping motor (SM). The revolution rate of the motor was controlled by a personal computer. As the screw volt rotated and loosed, the force applied to the screw decreased, and the force applied to the specimen was increased reversely.

For controlling the extensional rate of the specimen, the rigidity of the test machine was measured. The displacements at four points were measured using dial gages at room temperature, as shown in Fig.1. The number of revolutions of the stepping motor was 3.47×10^{-5} rpm. Fig.2(a) shows the displacement and the load measured by the cell. The displacement of DG1 is proportional to the time, however that of DG2 is not proportional due to the bending of the lever. The extension of the specimen was expressed by the difference between the displacements of DG3 and DG4. This value also was not proportional to the time. Fig.2(b) shows the displacements against the load. The curves for DG1, DG2 and DG3 deviates from the proportional relation. The curve of the extension of the specimen deviates when the load is smaller than about 600 kN. However, as the load exceeds 800 kN, the extension is proportional to the load. The deviation with the small load was caused by the clearances of the screw portions. The extensional rate of the specimen were converted from the rate of the displacement at the position of DG1, using the proportional ratio shown in this figure.

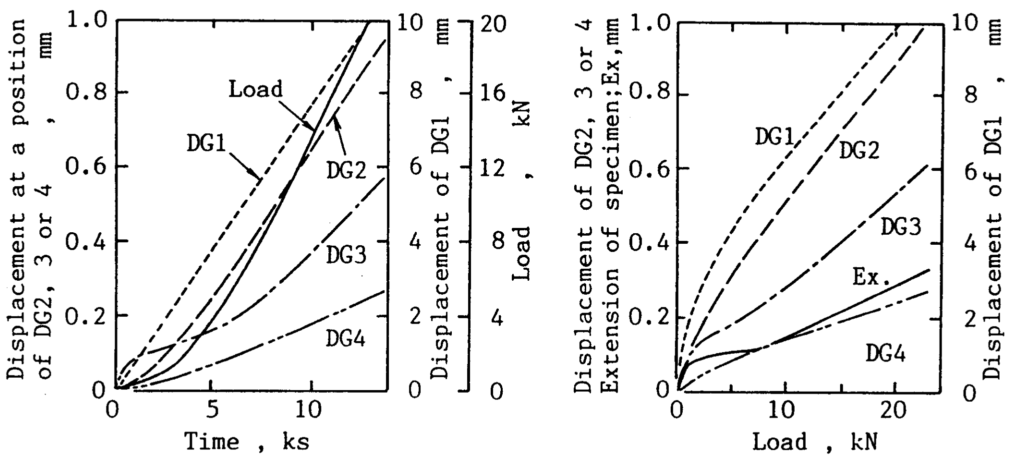

Fig.2 The elastic deformations of the testing machine under loading

2.2. Specimen

Steel specimen for the cracking test is shown in Fig.1. It was made from the plate of 2 1/4Cr–1Mo steel, of which chemical compositions are shown in Table 1. The axis of the specimen was laid on the rolling direction of the steel plate. The specimen has the circumferential notch of 0.5 mm depth in order to simulate the stress concentration of actual weldments. Stress concentration factor is about 3.

Table 1 Chemical compositions of 2 1/4Cr–1Mo steel

C	Si	Mn	P	S	Ni	Cr	Mo	Cu	As
0.14	0.16	0.56	0.006	0.002	0.03	2.17	0.90	0.01	0.004

To simulate the microstructure of HAZ, the simulator of weld–thermal–cycle was used. The specimen was heated with the heating rate of 92 K/s up to a given peak temperature. The peak temperature was changed from 927 to 1327 K. The temperature of specimen was kept for 1, 10 or 100 sec at the peak temperature for changing the austenite grain size of the specimen, and then rapidly cooled by water jet. The uniform microstructure of HAZ was made in the central portion of 20 mm in length of the specimen. The size of austenite grain is expressed by the terms of the mean linear intercept, in this paper. Fig.3 shows the effect of the processing conditions on the mean linear intercept (MLI) of austenite grain. The MLI is changed from 2 to 200 μm with the processing conditions. The MLI is linearly increased when the peak temperature rises with the constant holding time, and when the logarithm of the holding time is enlarged.

3. Results of the cracking tests

The creep rupture tests were carried out with the constant load, taking off the screw unit for controlling the position of the lever. For this tests, the dead load was directly applied to the specimen at room temperature, and heated up to the testing temperature for about half hour by the electric furnace. The temperature of the specimen was held at 873 or 823 K. The time to fracture is shown in Fig.4(a) and (b) for the testing temperatures of 873 and 823 K, respectively. In this figure, the number means the linear intercept of austenite grain of the specimen.

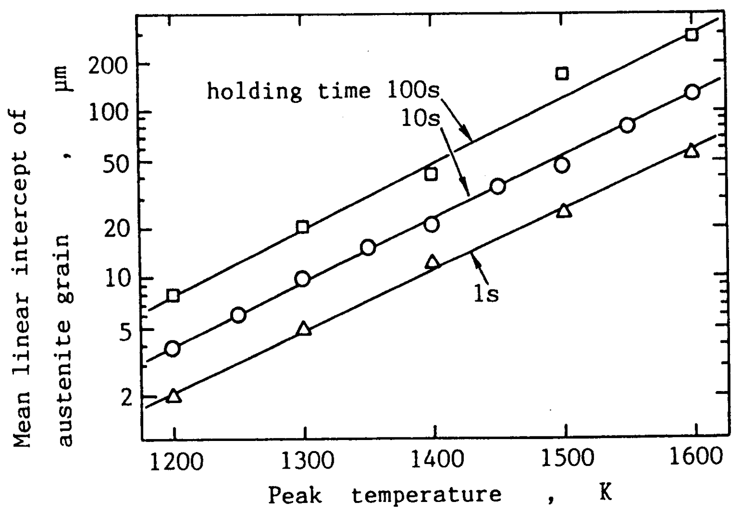

Fig.3 The effect of processing parameters on the size of austenite grain

The crack initiates in the short time for the coarsened austenite grain, for example, the MLI is 126 μm. The time to fracture is prolonged with the decreasing of the applied stress. The MLI is about 50 to 100 μm in the actual SMAW weld, and the initiating time of the reheat cracking is 1 to 20 hours. Therefore, these cracks can be classified to the reheat cracking. The times to fracture are plotted against the MLI value in Fig.5. Generally, the time is shortened with increasing the MLI. The dependence on the grain size is more remarkable with the high stress at lower temperature, such as the tests of 540 MPa at 823 K.

The observations by SEM certified that the specimens fractured by the intergranular mode. And the reduction area was as low as several percentage, independent of on the MLI value and the test temperature. The fraction of the grain boundary fracture could not be determined by the oxidized film on the surface.

Fig.6 shows the loading curves obtained by the cracking test with the constant extensional rate for the three size of austenite grains. The time is expressed in logarithmic scale. At first, the stress was zero, and then increased in proportion to the time, of which inclination was depended on the extensional rate of the specimen. In this figure, the stress seem to ne not proportional to the time because of the expression of time in logarithmic scale. Actually, the stress was proportional to the time till the stress reached to a point marked by a little open

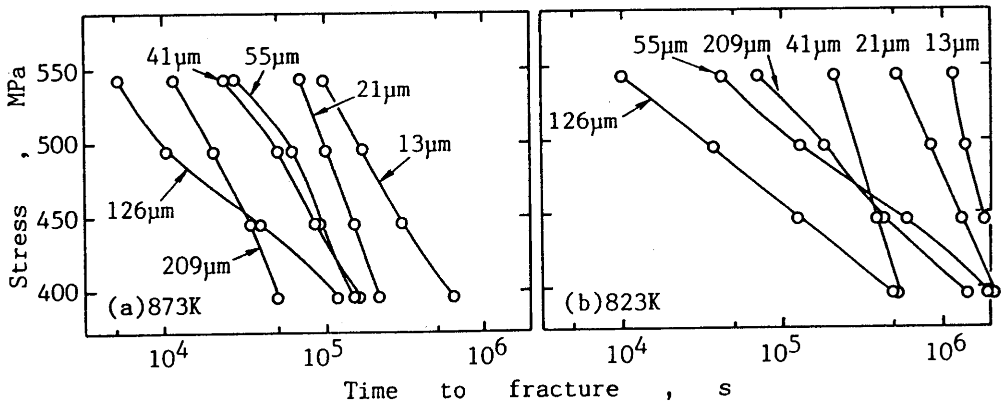

Fig.4 The time to fracture obtained by the constant load test

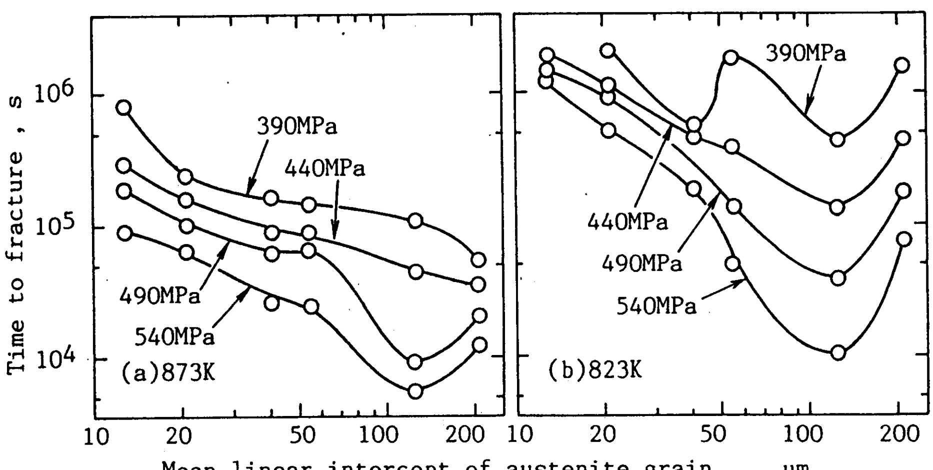

Fig.5 The effect of grain size on the time to fracture for the constant load test

circle. The stress was determined by the balance between the extensional rate and the elastic deformation of the specimen, including partly creep deformation.

The stress curves are classified into two types. The stress increased beyond the proportional limit (a open circle), and reached to the maximum level, marked by a small solid circle. In one case, the specimen fractured immediately at this time. It is imaged that the plastic flow occurred in a little amount between the proportional limit and the maximum level. In another case, the specimen did not fracture at the maximum level, and the stress decreased similar to the ordinary tensile test. The area of the notch root was decreased due to the occurrence of cracks or the local necking in the stress decreasing stage. The former was observed for the

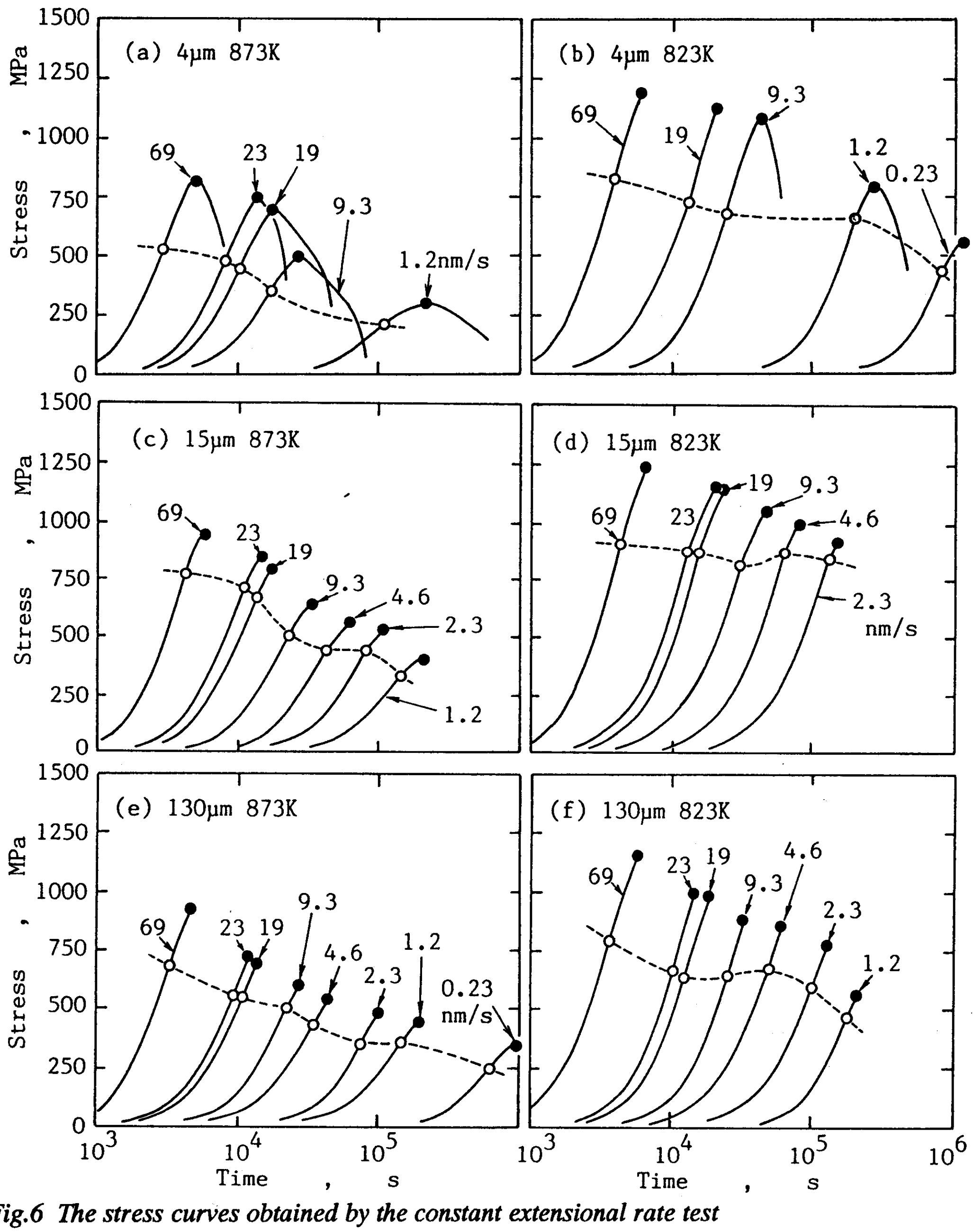

Fig.6 The stress curves obtained by the constant extensional rate test

larger austenite grain with higher extensional rate at low temperature. On the contrary, the later was observed for the small grain with lower rate at high temperature.

The proportional limit was lower for the testing temperature of 873 K than that of 823 K, and decreased with slowing the extensional rate, as shown by dotted lines in the figures.

4. The embrittling range of the grain boundary

The observations were carried out about the fracture mode and the reduction of area for the specimens fractured by the constant extensional rate test. Fig.7 shows the percentage of grain boundary mode in the fracture surface. The percentage of grain boundary fracture depends on the austenite grain size and the extensional rate. The grain boundary fracture is not recognized in the specimen of refined austenite grain, such as the MLI of 4 or 6 μm. The percentage is increased with coarsening the grain size. There exists the critical value of MLI,

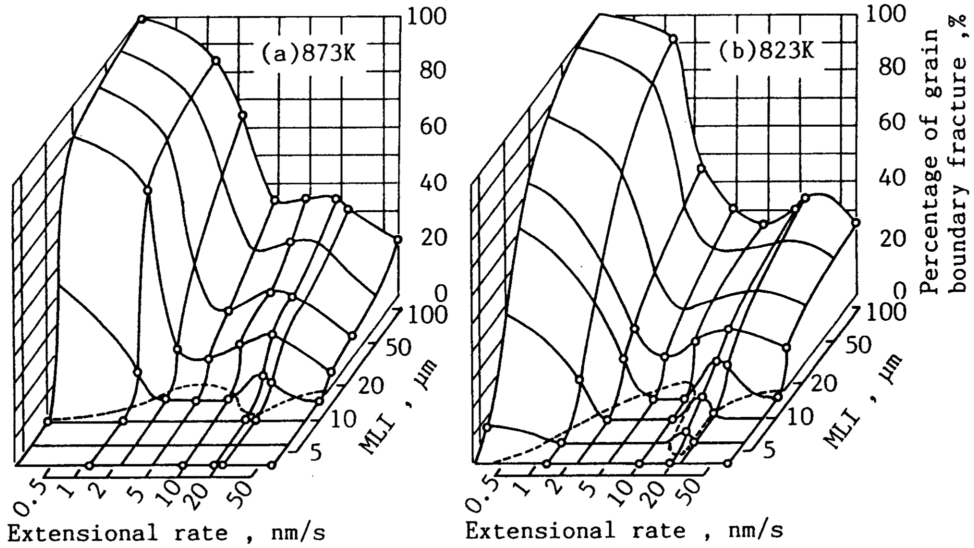

Fig.7 The percentage of grain boundary fracture for the constant extensional rate test

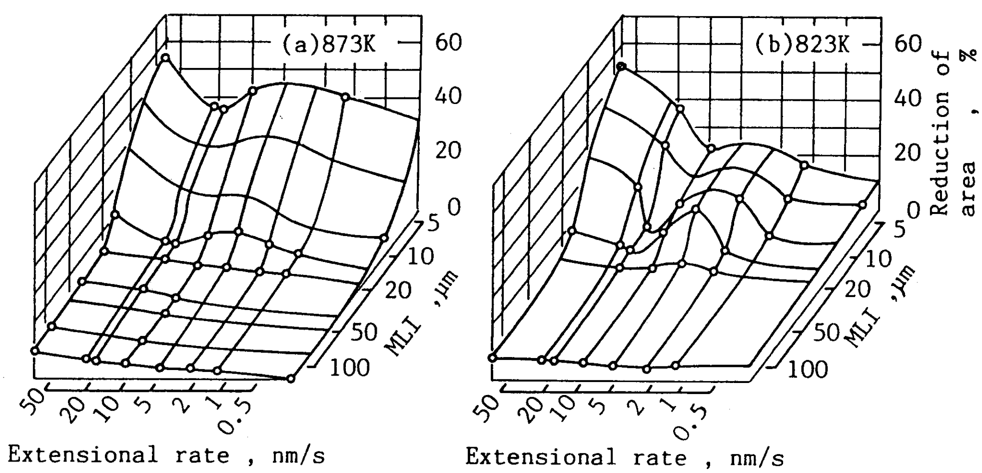

Fig.8 The reduction of area for the constant extensional rate test

below which the grain boundary fracture does not produce, as shown by a dotted curved line in this figure. The critical MLI is scarcely changed by the testing temperature, however, it is affected by the extensional rate. The critical MLI becomes small when the extensional rate is relatively high about 20 nm/s and very low, such as 0.02 nm/s.

The similar tendency was recognized in the change of the reduction of area, as shown in Fig.8. In this figure, the direction of axes are opposite to Fig.7.

As mentioned above, the converse relationship was recognized between the occurrence of grain boundary fracture and the reduction of area. The later will correspond to the elongation of the specimen at the fracture. Fig.9 shows the relation between the time to fracture (t_f) and the extensional rate (e_d). Plots laid roughly on each straight line corresponding to the grain size, and this fact means that the following equation will be applicable, because the figures are drawn on both logarithmic scales.

$$t_f \, e_d^{\,n} = K \quad K\text{: constant}$$

The value of index n is about 0.93, and independent of the grain size and the testing temperature. The constant K is decreased with increasing the grain size from 2.51×10^5 to 7.08×10^5. The above equation seems to be similar to a relation that a product of the strain rate and the time to fracture is constant. This similarity is very interesting from the view points of the considerations about the criterion for the grain boundary fracture. But there are some points of difference between two relations. At first, the variable of the extensional rate has a dimension of length/time, and does not strain/time. The specimen used in the present investigation had the notch, therefore, it was very difficult to define the gage length of the specimen. Secondary, two fracturing modes, grain boundary and ductile transgranular fractures, are included in the present results, on the other hand, the ductile fracture mode is only observed for the ordinary creep rupture testing.

The plots in Fig.9 are scattered near the corresponding lines. This scattering width is narrow mentioned above, however, required to be discussed. The elongation can be calculated from the data of the time to fracture and the extensional rate. The product of the extensional rate and the time to fracture means the elongation of the specimen at the fracture. If the time

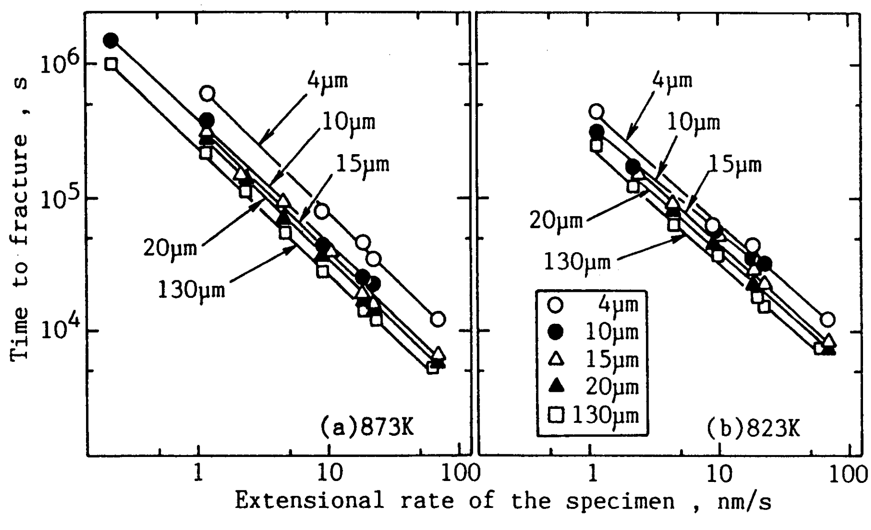

Fig.9 The relation between the extensional rate and the time to fracture

to fracture is expressed by the above equation, the elongation of the specimen should be kept on the constant value. Fig.10 shows the elongation with the extensional rate. The open marks mean that the fracture surface contains no grain boundary fracture, and the solid marks contains grain boundary fracture more or less. The elongation at the fracture is increased with decreasing the grain size for both testing temperatures, and it is also increased with increasing the extensional rate. However, the small hills are observed in the curves for the MLIs of 15 and 20 μm at 873 K and for the MLIs of 10 and 15 μm at 823 K. These plots correspond to the disappearance of grain boundary fracture shown in Fig.7.

Generally, the elongation is small for the specimens which contain the grain boundary fracture, shown by solid marks. However, the elongation in Fig.10 contains the deformation not only near the grain boundary, but also in grain interior, which may not be related to the grain boundary fracture. The authors suppose that the elongation of the specimen is dominated

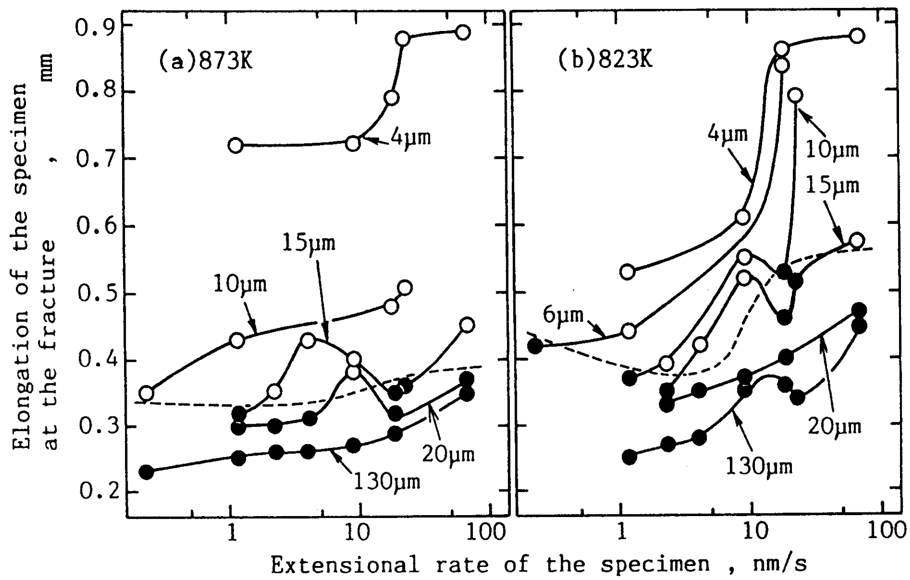

Fig.10 The elongation of the specimen at fracturing

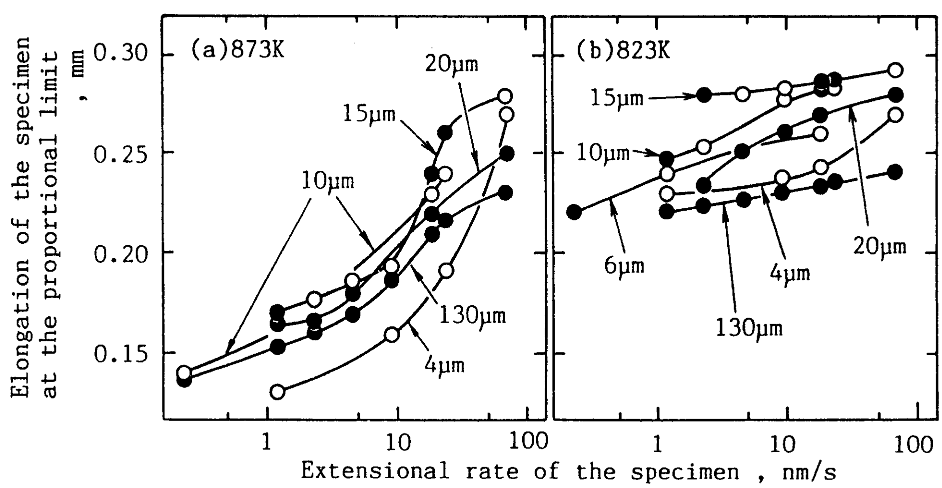

Fig.11 The elongation of the specimen at the proportional limit of the stress curve

by the deformation in grain interior, when the stress exceeds the proportional limit in Fig.6. That is, we thought that the grain boundary fracture initiated at this limit. Fig.11 shows the elongation of the specimen taking place till the stress reaches the proportional limit. In the case of the elongation at the proportional limit, these values are scarcely influenced by the grain size, however, it is increased with the extensional rate, especially for the data at 873K.

The grain boundary fracture can be simulated by both methods with the constant load and the constant extensional rate. The fracture surface obtained by the constant load test revealed only the grain boundary fracture, on the other hand, two grain boundary fractures were observed for the constant extensional rate test. This facts means that the grain boundary embrittled twice during the reheating. In the case of the constant load test, the second embrittlement was screened by the first embrittlement. Therefore, the constant extensional rate test will be useful to the investigations about the phenomena of grain boundary embrittlement.

5. Conclusions

The grain boundary fracture was investigated for the simulated weld HAZ of 2 1/4Cr–1Mo steel with various size of austenite grain, using the two types of cracking tests; the constant load test and the constant extensional rate test. The results are summarized as followings.

1) The grain boundary fracture was obtained by boyj cracking test methods. The grain boundary fracture was constant more than 80% for the constant load test, on the other hand, was increased with decreasing the extensional rate.

2) Two grain boundary fracture were observed by the constant extensional rate test.

3) The crack–initiating time was delayed as the austenite grain was refined for the constant load test, however the effect of grain size was small for the constant extensional rate test.

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