ELASTIC-PLASTIC FRACTURE TOUGHNESS OF HIGH PRESSURE STEEL TUBE

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ABSTRACT

It is necessary to estimate the K_{IC} value of a steel tube with a small diameter, in order to prevent the brittle fracture at the time of boiler water pressure proof test. Therefore, we have investigated the test method for obtaining the elastic-plastic fracture toughness (Jin value) by using the small-sized arc-shaped specimen cut from the cross section of an actual steel tube. Based on the above result, the Jin test result have been considered for the base metal of the 0.5Mo steel tube (JIS STBA 12) used for about 200,000 hours at 480℃ as a boiler super-heater and also for the test material made with synthetic thermal treatment to simulate the heat affected zone (HAZ) of the welded joint of a 2.25Cr-Mo steel tube (JIS STBA 24).

1 INTRODUCTION

It is necessary to evaluate the safety of the steel tube used for a high-pressure boiler to the brittle fracture during a hydraulic pressure proof test. However, there are only some examples about the above evaluation. In addition, the high-pressure steel tube with the external diameter of less than 50mm is used for a boiler etc, then, a specimen with an enough thickness is not able to be cut from the tube for obtaining the fracture toughness (K_{IC} value). Therefore, it is assumed that the fracture toughness (K_{IC} value) can be estimated from the elastic-plastic fracture toughness (Jin value) obtained by using a small-sized arc-shaped specimen cut from the cross section of an actual steel tube. On the first phase, it was confirmed that the three-point bending test by using the small-sized arc-shaped specimen could be performed reliably (Yamamoto[1]). It was especially confirmed that how much thickness of the specimen was required in order to realize a plane strain condition because of a long tube length. On the second phase, the following two tests were performed. Firstly, it is examined how much specimen creep damage would influence the Jin value by using the 0.5Mo steel tube (JIS STBA 12) used for about 200,000 hours at 480℃ as a secondary super-heater of a boiler for generator. Next, the Jin test was performed by using the test material made with synthetic thermal treatment to simulate the microstructure, grain size and hardness at the coarse grained zone of the HAZ of the welded joint in order to obtain the fracture toughness of the HAZ of the welded joint of a 2.25Cr-Mo steel tube (JIS STBA 24)(Yamamoto[2]).

2. TEST SPECIMEN AND Jin TEST

The tensile test results of test materials are shown in Table 1. Test materials are JIS STBA 12 (0.5Mo steel, * mark indicates the steel tube used for about 200,000 hours at 480℃ as a boiler super-heater), and JIS STBA 24 (2.25Cr-Mo steel). Microstructures of the materials are shown in Fig.2. A test specimen was cut from a tube as shown in Fig.1. A machined notch with the length of 4mm and a fatigue-cracked notch with the length of 1.5mm were made on the specimen so that the JSME standard (JSME[3]) and ASTM standard (ASTM[4]) might be satisfied. The elastic-plastic fracture toughness test was performed under the three-point bending condition as shown in Fig.3. ① in Fig.3 indicates a arc-shaped specimen, ② indicates supporting rollers, ③ indicates jigs for supporting the specimen, ④ indicates jigs for fixing the specimen, ⑤ indicates a temperature controlled bath , ⑥ indicates a bar for applying a compressive load. The test was performed under the constant displacement speed condition as 2mm/min. The test temperature was controlled using a electric heater, dry ice, ethanol and automotive coolant into the temperature controlled bath shown ⑤. The test was carried out at –30℃, 0℃, 20℃. J integration was calculated by measuring the area of a load-displacement curve of a test result according to the JSME standard (JSME[3]).

The heating-coloring method was used in order to measure a increment of a crack length. The specimen was heated at 300℃ for 5 min after Jin test. And then fracture surfaces were separated by brittle fracture at –70℃. It became clear that the status of the crack propagation could be grasped

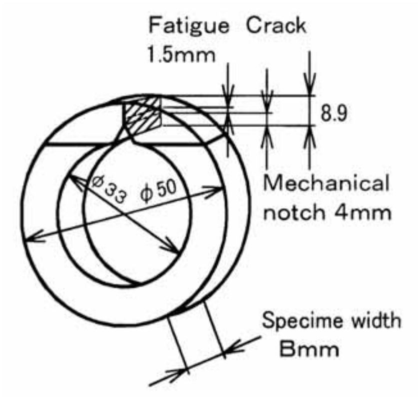


Figure 1: Arc shape specimen

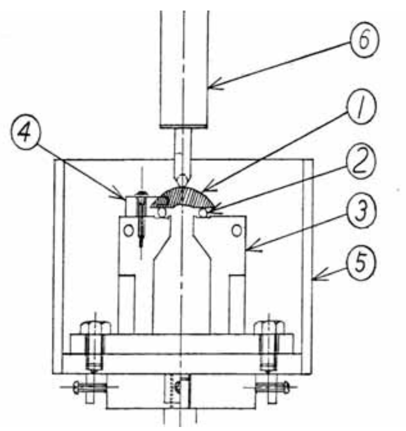


Figure 3: Jin testing apparatus

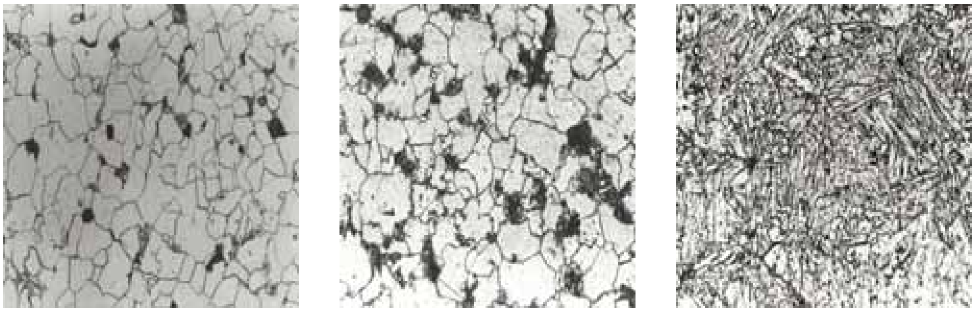
Table 1: Tensile test results

Materials	Spec. Diam mm.	σ_y MPa	σ_b Mpa	σ_T Mpa	δ %	φ %
STBA12	4.03	325.6	455.0	950.3	31.4	69.7
STBA12*	4.03	297	451	1218	42.9	74.9
STBA24	3.98	343.0	470.4	—	61.0	—
HAZ	3.98	520.4	640.9	—	39.4	81.7

quite clearly as shown in Fig.4. The increment of a crack length is the average value of crack lengths at positions of (3/8)B, (4/8)B and (5/8)B in the thickness direction (B : thickness of the specimen) observed using a measuring microscope and a scanning electron microscope. Figure 5 shows examples of fracture surfaces of specimens for the elastic-plastic fracture toughness test observed using a scanning electron microscope. The white area on the center part of Fig.5(b) is a stretch zone. The width of the stretch zone was obtained by measuring the value at positions of (3/8)B, (4/8)B and (5/8)B and averaging these values same as the increment of a crack length. R curves were decided based on the relation between a J integration value and an increment of a crack length by using the above result. And the width of the stretch zone does not increase even if the crack length increases. That is to say, the critical stretch zone which shows the constant value can be observed. The Jin value is the intersection point between the R curve and the critical stretch zone according to the above phenomenon. This Jin value is the J integration value in case a crack begins to propagate. In this study, the Jin value was decided based on the above method.

3. SPECIMEN THICKNESS (B) AND PLANE STRAIN CONDITION

In this chapter, the relation between a Jin value and a specimen thickness (B), and the plane strain condition for crack propagation are considered (Yamamoto[2]). STBA 12 was tested changing a specimen thickness (B) with 8mm, 4mm and 2mm. All tests were performed at –30℃.The crack propagation shape was observed using the heating-coloring method. The shape can be seen clearly as shown in Fig.4. The flat tip shape of the crack propagation is observed on the specimen with wide thickness (B). But on the specimen with narrow thickness (B), the triangular crack propagation shape is observed. The rate of the plane stress area in a cross section of the specimen becomes large when the specimen thickness (B) for the fracture toughness test becomes narrow, and therefore the inclining fracture occurs easily. On the other hand, the rate of the plane strain area in a cross section of the specimen becomes large when the specimen thickness (B) becomes wide. Moreover, the relation between the calculated result of J integration value and the specimen thickness (B) can be obtained as shown in Fig.6. The Jin value increases and is saturated with increasing



(a) STBA12 (b) STBA24 (c) STBA24 HAZ

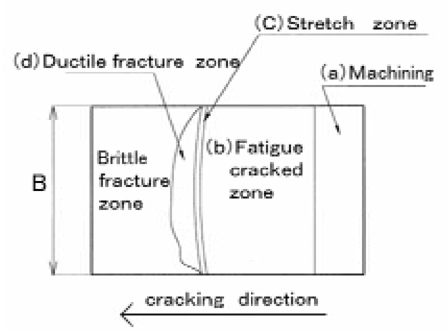
Figure 2: Micro structure

100μm

the specimen thickness (B). From the above result, the specimen thickness (B) larger than 6mm is required in order to obtain the Jin value of the steel tube.

4. AGED BOILER TUBE AND Jin VALUE

Commercial boilers are working under the high-temperature and high-pressure conditions, and many of them have worked for 20 to 30 years. It is probably considered that there are some super-heater tube and re-heater tube having creep damage. The boilers have to undergo the hydraulic pressure test with 1.5 times normal pressure every periodic survey. And consequentially, it is necessary to consider about a brittle fracture in case the tube has a creep damage. Therefore, in this study, the Jin test was performed by using the STBA 12 steel tube used at 480℃ for about 200,000 hours as a boiler super-heater. The specimen with the thickness of 4mm was used for the test. Figure 7 shows the comparison between the test results of the steel tube used for about 200,000 hours as a boiler super-heater and the virgin tube. It became clear that the material hardly deteriorates under the creep condition of the steel tube used for about 200,000 hours at 480℃ as a boiler super-heater.





(b) B=2mm -30°C(×2)　(c) B=4mm -30°C(×2)　(d) B=8mm 20°C

Figure 4: Crack shapes of Elastic-Plastic toughness Jin specimen (STBA12)



(a) Fatigue cracked zone　(b) Stretch zone　(c) Ductile fracture zone

(STBA, B=8mm, 0°C)

10μm

Figure 5: Fracture surface by SEM (cracking direction : upper to down)

5. Jin VALUE OF TEST MATERIAL SYNTHETIC HAZ OF WELDED JOINT

There are little actual data about the fracture toughness of the HAZ of the welded joint for Cr-Mo steels. In addition, when a crack propagates from the HAZ of a welded joint, the crack often pass thorough a coarse grained zone. Therefore, many kinds of complex phenomenon affect on the brittle fracture of the HAZ of a welded joint. In this study, as the first phase investigation, the material corresponding to the material in the coarse grained zone at the HAZ of the welded joint of a 2.25 Cr-Mo steel tube (JIS STBA24) was made with synthetic thermal treatment. The Jin test was performed by using the above material, and then the test result was compared with the test result of a base metal of a JIS STBA 24 steel tube. Problems place at boiler main steam pipe and re-heater pipe on the actual boiler. Bainite and martensitic duplex-microstructure was observed in the coarse grained zone from the result of the welding test under the same condition as the actual welded joint. The grain size at the coarse grained zone was 100µm, and the hardness was HV200. A steel tube (JIS STBA 24) with the external diameter of 50mm, with the internal diameter of 33mm and with the length of 600mm was heat-treated using the synthetic heat cycle system with high-frequency induction heating. The heat treatment condition was decided after the pretest in consideration of the continuous cooling transformation diagram (CCT curve) in order to simulate the heat cycle on the welding test result. From the above pretest result, the following heat treatment condition was decided. The maximum temperature was 1300℃ and the holding time was 15 seconds. Air cooling was conducted so that the cooling time between 800℃ to 500℃ might become 30 seconds. Under the above heat treatment condition, the microstructure as shown in Fig.2(C) was able to be obtained. The grain size of the microstructure was 100 to 150µm and the hardness was HV240. The Jin test was performed using the above material with the 8mm thick (B) specimen. The tensile test results of a base metal of the JIS STBA 24 steel tube and the HAZ of the welded joint of a 2.25 Cr-Mo steel tube (JIS

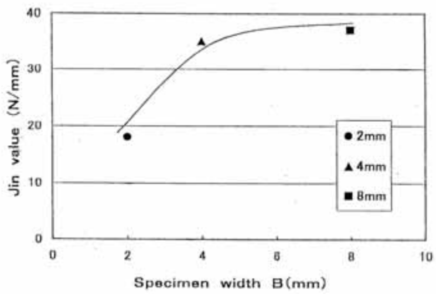


Figure 6: Specimen width ; B and J

(STBA12, -30°C)

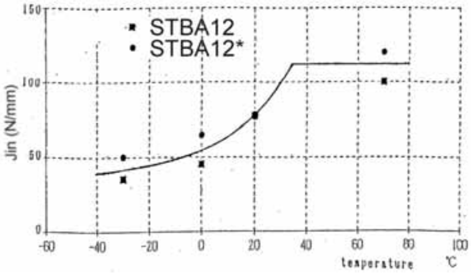


Figure 7: Temperature and Jin

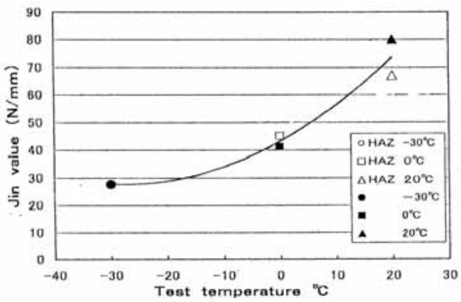


Figure 8: Test temperature and Jin

STBA24) made with synthetic thermal treatment were shown in Table 1. Figure 8 shows the Jin test result. It was predicted that the Jin value of the HAZ material decreased as compared with the base metal. However it became clear from Fig.8 that the both values did not almost have a difference. In addition, the paper which reported the Jin value of the actual welded joint of a JIS STBA 24 steel tube by performing a fracture toughness test could not be found. However, for example, some papers (Yajima[5]) report that the Charpy impact test result of a YP47 steel plate for a marine structure, which has the almost same strength of σ_y and σ_B as that of JIS STBA 24, is little more than the result of a base metal. The above reports can suggest the validity of the Jin value obtained in this study.

6.CONCLUSION

(1) The test method for obtaining the Jin value of the high-pressure steel tube with the external diameter of less than 50mm was investigated. As a result of the investigation, it became clear that the Jin value under the plane strain condition could be obtained by using the arc-shape specimen with the thickness of more than 6mm.

(2) The Jin value of the steel tube (0.5Mo steel tube, JIS STBA 12) used for about 200,000 hours at 480℃ as a super-heater of a boiler had no deterioration from that of a virgin steel tube.

(3) The material simulated to the HAZ of the welded joint of a 2.25Cr-Mo steel tube (JIS STBA 24) had almost the same Jin value as the base metal of a JIS STBA 24 steel tube.

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REFERENCE

[1] Yamamoto,S., Murasaki,Y., ; Elastic-Plastic Fracture Toughness of steel Tube, Trans. JSME ,SerA vol66. No644, P791-795, (2000).(in Japanese)

[2] Yamamoto,S., Taga,H., ; Elastic-Plastic Fracture Toughness of Boiler Tube, Trans. JSME, SerA. (2004) under Publishing. (in Japanese)

[3] JSME ; Standard Method of Test for Elastic-Plastic Fracture Toughness J_{IC}, JSME S001-(1992).

[4] ASTM ; Standards Test Method for Plane-Strain Fracture Toughness of Metallic Materials, ASTM E399-90, (1992).

[5] Yajima,H., Tada,M., et al; West Japan Soc.Naval Architects No73, P192-200, (1987). (in Japanese)