INTERNAL PRESSURE FATIGUE RUPTURE TEST ON FUEL CLADDING FOR FAST REACTOR

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SUMMARY

This paper shows the result of the internal pressure fatigue rupture test that was conducted at high temperatures on fuel cladding for the fast experimental reactor, "JOYO", which was under development by the Power Reactor and Nuclear Fuel Development Corporation. The purpose of this test is to clarify the internal pressure fatigue characteristics of the fuel cladding, thereby obtaining the allowable stress of the fuel cladding so that it may be used in the fuel design.

The fuel cladding was made of Type AISI 316 stainless steel and its dimensions were 5.60 mm I.D. and 0.35 mm wall thickness.

The test apparatus was developed to give internal pressure cycles into tubular specimens under constant high temperature or coinciding with temperature cycles fully automatically.

The fatigue rupture test was conducted on tubing section and end.

1. Introduction

The design of a fuel cladding tube in LMFBR has several features different from those of the design of a reactor vessel and other structural components. The required life time of the cladding tube is usually shorter than that of the vessel, and the failure of a few tubes in the core does not always bring a fatal catastrophe on nuclear systems. However, the cladding tube is opposed to very high temperature and strong irradiation, and is subjected to high internal pressure due to accumulation of fission gas. Further it may be suffered from swelling of fuel pellets during operation.

Therefore, the fuel cladding tube must be designed so as to keep safety assurance under such severe operating conditions from the standpoints of both structural integrity and functional requirements. Considerations of high temperature creep and fatigue under strong irradiation are most important.

The main purpose of the present work is to obtain some fundamental data for the design of the cladding tube in LMFBR, particularly on low-cycle fatigue strength of the tube under cyclic internal pressure at high temperature. The work was performed as a part of the development program of LMFBR under sponsorship of Power Reactor and Nuclear Fuel Development Corporation.

2. Experiment

2.1 Test Specimen

The test specimen is a thin tube of 5.60 mm in inner diameter and 0.35 mm in wall thickness. The material is type AISI 316 stainless steel cold worked by about 10 % in reduction of area. Table 1 shows the chemical composition and the mechanical properties of the material. Fig. 1 shows the temperature dependency of the properties in terms of yield pressure and burst pressure of the tube. Fig. 2 gives the configuration of the specimen. Both ends of the tube, 150 mm in length, are sealed with plugs by heliarc welding. The small hole through the big plug at one end is used for the passage of argon gas inside the specimen. Fig. 3 shows metallographic structure of the tubing section and the heat affected zone adjacent to the welding bead. Remarkable grain growth is observed in the heat affected zone.

When the fatigue test was aimed at the tubing section, the end of the tube including the plug and the heat affected zone was reinforced with a ring-shaped jig for avoiding crack initiation at the end plug weld. On the other hand, when the fatigue test was aimed at the end plug weld, the end part was placed in the middle of the heating furnace, while the other end with the tubing plug having the argon gas passage was propected with a reinforcement ring.

2.2 Test Device

Figure 4 shows schematic view of the test device. The specimen is heated by a tube-type electric furnace. Argon gas is used for internal pressure medium inside the tube and for cover gas preventing the tube from oxidation. The regulation of temperature and pressure is controlled by an automatic system.

2.2.1 Isothermal High Temperature Fatigue Test

Figure 5 (a) shows the scheme of the wave form of pulsating pressure cycle in the isothermal fatigue test. The pressure of argon gas which is supplied from a gas cylinder is raised by the pressure intensifier and held in the accumulator. The inlet diaphragm valve is opened by an indication of the test program, and the specimen is pressurized up to the maximum pressure which is set up beforehand by a pressure reducing valve. If, by some reason, the internal pressure might overcome the limit value, excess gas is released through the maximum pressure holding valve. After holding the internal pressure at a specified value for a specified period t_{hu}, the inlet diaphragm valve is closed and the outlet diaphragm valve is opened by an indication of the test program. Then, argon gas included in the tube is released through the minimum pressure holding valve until the internal pressure falls to the lower limit value.

When the specimen is failed, a limit switch on the protecting tube is operated by the increase of pressure inside the tube and the apparatus is switched off. Number of cycles to failure is recorded on a cycle counter.

The period of a cycle without the hold-time of the maximum pressure is between 20 and 30 seconds. The minimum pressure 5 kg/cm^2 is for prevention of backward air flow into the apparatus. The hold-time of the minimum pressure was taken as 60 seconds on account of the capacity of the pressure intensifier. The test temperature and the hold time of the maximum pressure were varied according to the test program.

2.2.2 Thermal Cycle Fatigue Test

Figure 5 (b) shows the scheme of the wave forms of temperature and pressure in the thermal cycle fatigue test. The specimen is heated by a furnace whose temperature is kept constant at the maximum value. When the specimen attains the maximum temperature, the pressure cycle acts synchronously. Then the furnace is withdrawn by an air piston which is driven by the program indication. When the temperature of the specimen falls to the specified minimum value, the furnace is put back in its place by the air piston and the specimen heated up again.

The minimum temperature is taken as 250°C according to the sodium temperature during the shut-down of the experimental FBR, "JOYO", which is now under construction in its research laboratory of Power Reactor and Nuclear Fuel Development Corporation. About 20 minutes is required for the period of the temperature cycle t_{tc}.

The length of the range of an even temperature in the furnace was about 180 mm at 600°C within the difference of ±2.5°C, and about 190 mm at 800°C within ±3°C. Table shows the accuracy of the control of temperature and pressure in the isothermal and thermal cycle tests.

2.3 Test Conditions

The whole test program of the present work is summarized in Table 3. In the fatigue tests of the tubing section, the test temperature in the isothermal tests and the maximum temperature in the thermal cycle tests were taken as 600, 650 and 700°C. The hold-time of the maximum pressure t_{hu} was varied from 0 to 300 minutes.

Fatigue tests of the end plug weld were performed at 650°C with the hold-time of the maximum pressure t_{hu} ranging from 0 to 30 minutes.

The maximum pressure of pulsating pressure cycle was taken below the yield pressure which had been tested beforehand as shown in Fig. 1.

3. Results and Discussion

3.1 Fatigue Strength of Tubing Section without Hold-Time

Figure 6 shows the results of the isothermal and thermal cycle tests without the hold-time of the maximum pressure. There is observed no more difference than errors of experiments between the results mentioned above.

The result for each test temperature shows essentially a linear relationship between the maximum pressure and number of cycles to failure on log-log coordinates at least over the range from 1 to about 5,000 cycles. The results are expressed by the following empirical equations :

at 600°C $$N_f = \left(\frac{\sigma_t}{46.6}\right)^{-19.8} \quad (1)$$

at 650°C $$N_f = \left(\frac{\sigma_t}{40.6}\right)^{-17.3} \quad (2)$$

at 700°C $$N_f = \left(\frac{\sigma_t}{35.6}\right)^{-14.4} \quad (3)$$

where N_f : number of cycles to failure
σ_t : circumferential hoop stress $= \frac{P_u D_i}{200W}$ (kg/mm²) (4)
P_u : maximum pressure (kg/cm²)
D_i : inner diameter (mm)
W : wall thickness (mm).

Figure 7 shows the results shown in Fig. 6 in terms of stress amplitude S_a versus number of cycles to failure. The stress amplitude S_a is given in this case by the following equation :

$$S_a = \frac{(P_u - P_l)D_i}{400W} \quad (5)$$

where P_l : minimum pressure (kg/cm²).

The broken lines in Fig. 7 show the fatigue design curves for high alloy steels and N_i-C_r-F_e alloy at 590°C and 650°C derived from the results of a strain-controlled fatigue test (ASME [1]). For the convenience of comparing the results of stress- and strain-controlled fatigue tests, the provisional design curves were derived directly from the fatigue curves by applying tentatively a factor of safety of 2 on the stress amplitude as shown by the solid lines in Fig. 7.

In a strain-controlled fatigue test, stress amplitudes S_a is given by the following equation :

$$S_a = \frac{1}{2}\varepsilon_t E = \frac{1}{2}\varepsilon_e E + \frac{1}{2}\varepsilon_p E \quad (6)$$

where ε_t : total strain range
ε_e : elastic strain range
ε_p : plastic strain range
E : Young's modulus.

The provisional design curves derived from the present work appear to show approximately the elastic component of the fatigue strength of the strain-controlled.

3.2 Effect of Hold-Time on Fatigue Strength

Figure 8 shows the effect of the hold-time of the maximum pressure on the fatigue strength of the tubing section and the end plug weld, where the test temperature is 650°C. The tubing section and the end plug weld have the approximately same value in the fatigue strength.

The effect of the hold-time is remarkable. The creep sub-group coordinated by Power Reactor and Nuclear Fuel Development Corporation has investigated the creep rupture strength of the same batch of cladding tube as that supplied to the present work (Yoshida [2]). The creep rupture strength of the tube subjected to constant internal pressure is shown in Fig.9 by a band of which the upper and lower broken lines illustrate the amount of scatter of the creep rupture data.

The total time to failure t_f is given in fatigue tests as follows :

$$t_f = N_f t_{hu} \qquad (7)$$

The results of the tests in which the hold-time of the maximum pressure were 3, 30 and 300 minutes are plotted in Fig. 9 in terms of the maximum pressure versus the total time to failure. They agree faily well with the creep rupture curve.

The linear cumulative damage law is widely applied for predicting the effect of simultaneous fatigue and creep on life.

$$\frac{N_f}{N_{fo}} + \frac{t_r}{t_{ro}} = 1 \qquad (8)$$

where N_{fo} : number of cycles to failure in pure fatigue test

t_{ro} : rupture time in pure creep test.

Figure 9 means that at 650°C, the fatigue fraction in eq. (8) N_f/N_{fo} is approximately zero and the creep fraction t_r/t_{ro} is approximately 1 at least when the maximum pressure is below the yield of the tube and the hold-time of the maximum pressure is longer than 3 minutes. Namely, the effect of the hold-time of the maximum pressure on the fatigue life of the tube can be predicted approximately by the mere creep under the same constant pressure.

3.3 Fracture Behaviour

3.3.1 Tubing Section

Figure 10 (a) shows the appearance of specimens failed under the conditions where the test temperature and the hold-time of the maximum pressure were taken as 650°C and 30 minutes respectively. All specimens failed under other conditions show the similar opening to Fig. 10 (a). Figure 11 shows an example of photomicrographs of the transverse cross section at an end of the rupture opening. Many cavities or cracks are observed at grain boundaries and small cracks are recognized on the inner surface. The through crack appears mainly intergranular and partly transgranular.

Figure 12 shows the relationship between number of cycles to failure and the circumferential elongation e_f given as follows :

$$e_f = \frac{l_f - l_o}{l_o} \qquad (9)$$

where l_o : circumferential length of tubing before testing
l_f : circumferential length at rupture opening.

The circumferential elongation decreases as number of cycles to failure increases, however it appears to become constant over the range above 1,000 cycles. The reduction in ductility might be induced from the cavity or crack formation as observed in Fig. 11. However the reason may be, this result shows that the tube deteriorates in ductility up to 1 ~ 3 % under severe mechanical load at elevated temperature even without irradiation.

3.3.2 End Plug Weld

Figure 10 (b) shows the appearance of specimens failed at end plug weld under the conditions where the test temperature and the hold-time of the maximum pressure were taken as 650°C and 30 minutes respectively. Four of six plugs were torn off on fracture and two of them were failed with small leakages. Figure 13 is an enlarged photograph of the small leakage observed on the outer surface of a failed specimen. It shows increase in diameter and crack initiation in the heat affected zone adjacent to the welding bead. Judging from the photograph, the appearent fatigue strength of the end plug weld shown in Fig. 8 means the strength of the heat affected zone. The end plug weld must have at least higher fatigue strength than the heat affected zone.

4. Conclusions

The fatigue strength of cladding tubes for LMBFR, which were subjected to cyclic internal pressure under both isothermal and thermal cycle conditions, was investigated over the low-cycle range up to 5,000 cycles. The effect of the hold-time of the maximum pressure on fatigue lives of the tubing section and the end plug weld was also investigated at 650°C.

The results are summarized as follows.

(1) The fatigue strength of the tubing section under isothermal and thermal cycle conditions is shown by a linear relationship between the maximum pressure and number of cycles to failure on log-log coordinates at each test temperature. The fatigue strength under the isothermal conditions was approximately equal to that under the thermal cycle conditions where the maximum temperature was equal to the temperature in the isothermal test.

(2) The results mentioned above are expressed by the following empirical equations :

at 600°C $$N_f = \left(\frac{\sigma_t}{46.6}\right)^{-19.8}$$

at 650°C $$N_f = \left(\frac{\sigma_t}{40.6}\right)^{-17.3}$$

at 700°C $$N_f = \left(\frac{\sigma_t}{35.6}\right)^{-14.4}$$

(3) The relationship between the maximum pressure and the total time to failure in the cyclic test agrees faily well with the creep rupture curve of the tube subjected to a constant internal pressure which is equal to the maximum pressure in the cyclic test, when the maximum pressure is below the yield of the tube and the hold-time of the maximum pressure is longer than 3 minutes.

(4) The end plug weld has the approximately same fatigue strength as the tubing section. In the fatigue fracture at the end plug weld, cracks initiate in the heat affected zone.

(5) The circumferential elongation at rupture openings decreases up to 1 ~ 3 % as number of cycles to failure increases.

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References

1. ASME, Interpretation of ASME Boiler and Pressure Vessel Code, Case 1331-4 (1967).
2. YOSHIDA, S., "Internally pressurizing creep rupture test on fuel cladding tube for the experimental fast reactor", Internal report of Power Reactor and Nuclear Fuel Development Corporation, S N241 72-43 (1972).

Table I Chemical composition and mechanical properties of investigated material

Chemical composition

Items \ Elements		C	Si	Mn	P	S	Cu	Ni	Cr.	Mo	Co	B	N
Spec. (%)	min	0.04	—	—	—	—	—	11.00	16.00	2.00	—	—	—
	max	0.08	0.75	2.00	0.03	0.03	—	14.00	18.00	3.00	0.10	0.001	0.035
Check analysis (%)		0.06	0.58	1.54	0.003	0.014	0.22	13.09	17.05	2.41	0.02	0.0003	0.026

Mechanical properties

Items \ Items of mechanical properties	Tensile properties at room temp.			Tensile properties at 650°C			Vicker's hardness
	Yield strength (kg/mm^2)	Ultimate tensile strength (kg/mm^2)	Elongation (%)	Yield strength (kg/mm^2)	Ultimate tensile strength (kg/mm^2)	Elongation (%)	
Specification	> 40	> 60	> 25	> 20	> 30	> 15	—
Measured values	58.8	72.0	31	30.8	42.4	30.5	276

Table II Accuracy of control of temperature and pressure

Type of test	Control item	Upper	Lower
Isothermal fatigue test	Temperature	+3° C −1° C	—
	Pressure	± 4 %	± 20 %
Thermal cycle fatigue test	Temperature	+10°C − 5°C	± 5°C
	Pressure	± 4 %	± 20 %

Table III Whole test program

Object of test	Type of test	Test temperature (°C)	Hold time (min)	Target number of cycles to failure
Tubing section	Isothermal fatigue test	600	0	100, 200, 400, 800, 1500, 3000
		650	0	ditto
		700	0	ditto
		650	3	ditto
			30	ditto
			300	30, 60, 130, 300
	Thermal cycle fatigue test	250 ⇄ 600	0	100, 200, 400, 800, 1500, 3000
		250 ⇄ 650	0	ditto
		250 ⇄ 700	0	ditto
End plug weld	Isothermal fatigue test	650	0	ditto
			3	ditto
			30	ditto

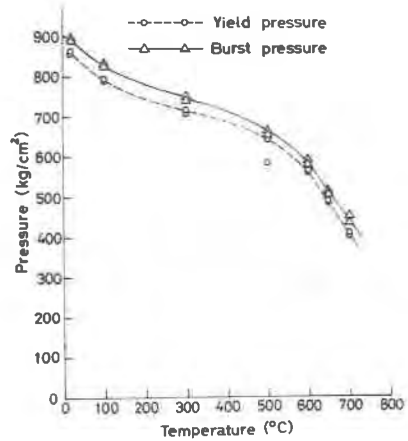

Fig. 1 Strength of investigated material under internal pressure

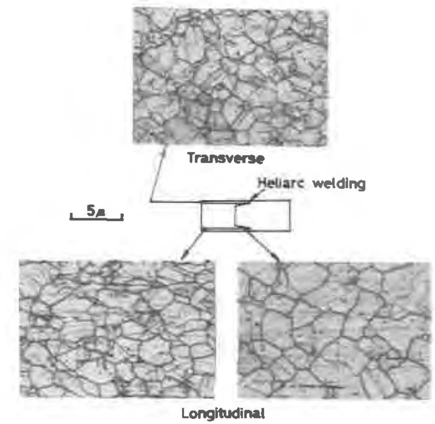

Fig. 3 Metallographic structure of specimen

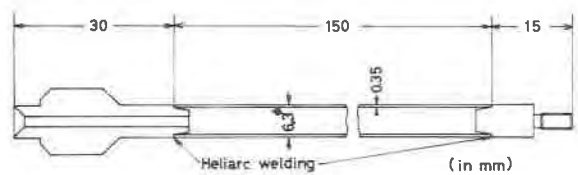

Fig. 2 Configuration of specimen

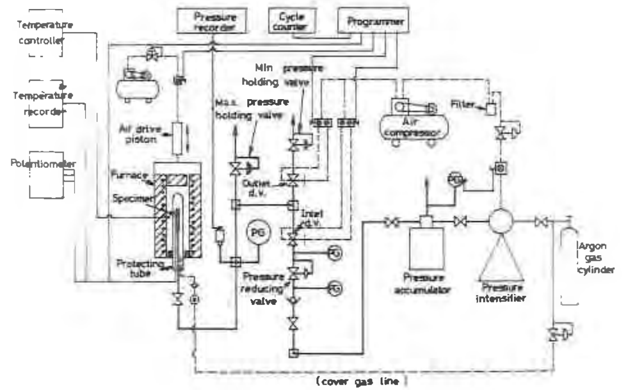

Fig. 4 Schematic view of internally pressurizing fatigue apparatus

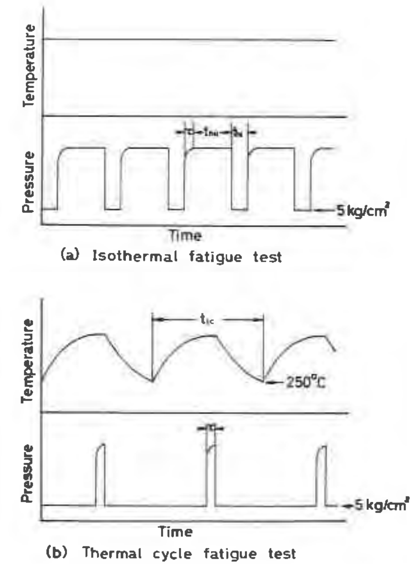

Fig. 5 Scheme of wave forms of temperature and pressure

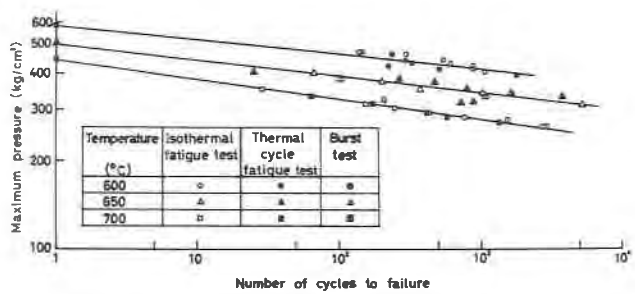

Fig. 6 Fatigue strength of tubing section under isothermal and thermal cycle conditions

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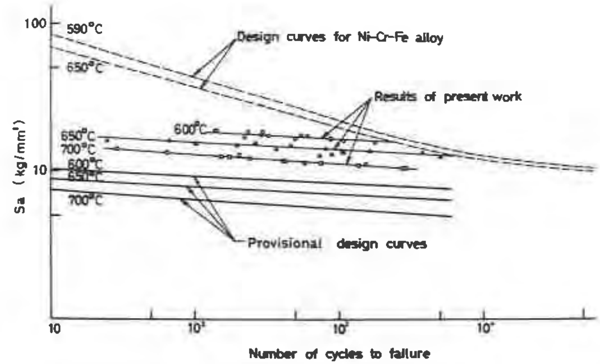

Fig. 7 Fatigue curves of tubing section

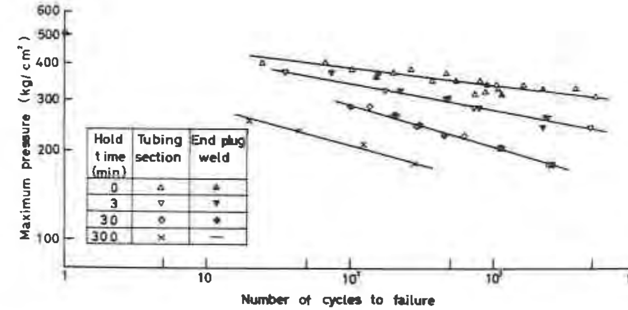

Fig. 8 Effect of hold-time on fatigue strength of tubing section and end plug weld (test temperature : 650°C)

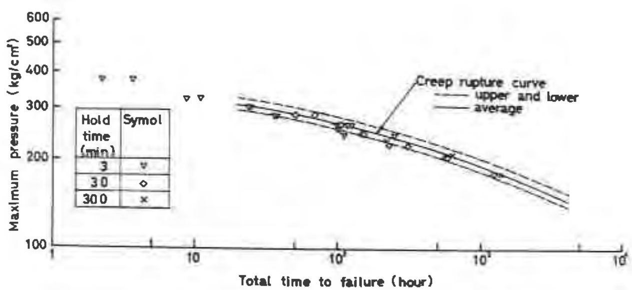

Fig. 9 Comparison of fatigue strength with internally pressurizing creep rupture curve (test temperature : 650°C)

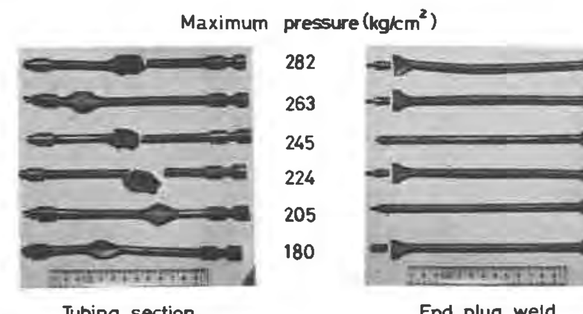

Fig. 10 Appearance of ruptured specimens (test temperature : 650°C, hold-time of maximum pressure : 30 minutes)

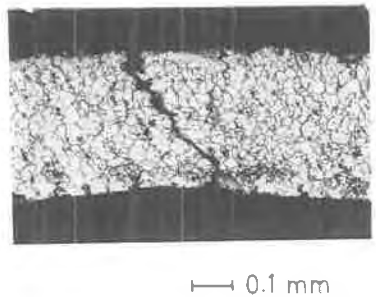

Fig. 11 Photomicrograph of transverse cross section at end of rupture opening

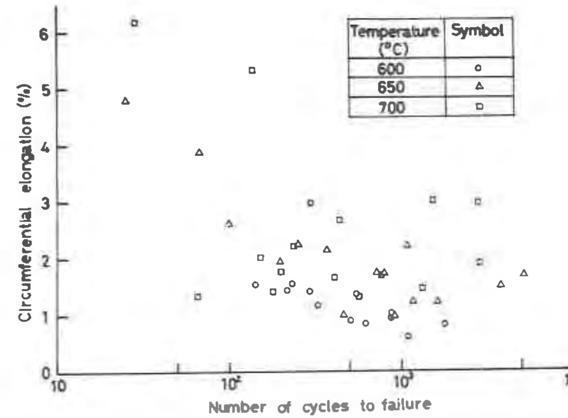

Fig. 12 Relationship between circumferential elongation and number of cycles to failure

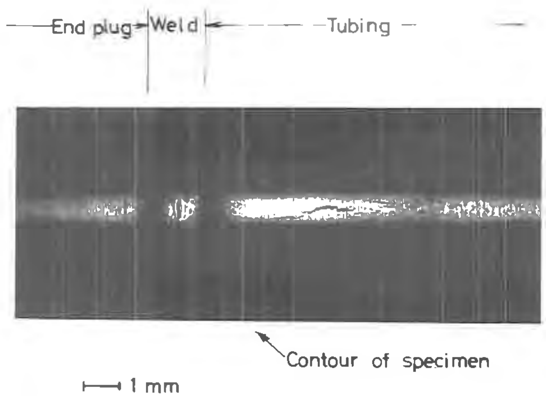

Fig. 13 Appearance of small leakage at heat affected zone

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