STRUCTURAL BEHAVIOR OF WELDED SUPERALLOY CYLINDER WITH INTERNAL PRESSURE IN HIGH TEMPERATURE ENVIRONMENT

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Summary

Hastelloy X is one of the promising heat resistant alloys in very high temperature use such as HTGR. In order to investigate the structural behavior of a superalloy cylinder in high temperature environment, steady and cyclic creep tests with internal pressure were performed on Hastelloy X cylinders with and without a circumferential TIG weld joint at 800 – 1000°C. The tests showed that the creep rupture strength of the TIG welded cylinder was much lower than that of the non-welded cylinder, and the strength reduction by the weld joint increased with temperature increase, while such creep rupture strength reduction by the weld joint was not observed in uniaxial creep tests. Creep failure of the TIG welded cylinders occurred always in the weld metal in the form of many longitudinal cracks. The failure occurred before the creep of the cylinder attained the tertiary stage. Diametral expansion of the TIG welded section of the cylinder was less than 5%, whereas that of the base metal section, where no crack was found, was approximately 10%. The diametral creep rate of the welded section was much lower than that of the base metal section of the cylinder.

In order to improve the creep strength of the TIG welded cylinder, welding procedure with miscellaneous weld metals was investigated. An improvement was obtained by Incoloy 800 and the modified-Hastelloy X as the filler metal. The creep rupture strength and ductility of the welded cylinders with these filler metals became higher to a certain extent than that of the conventional TIG welded cylinder. As another attempt to the improvement, electron beam welding was applied to the Hastelloy X cylinder. The result was so good that the creep rupture strength and ductility at 1000°C were almost equal to those of the non-welded cylinder.

It is noticed that in case of welded components with weld metal of low ductility at elevated temperatures such as in the conventional TIG welded Hastelloy X cylinder, data obtained by uniaxial creep tests on specimens welded in the same condition can hardly give the basis of the assessment of rupture strength of the welded components.

This investigation is a work made in a committee with cooperation of K. Kobatake, K. Sato and M. Sonobe of Kawasaki Heavy Industries, K. Kishimoto and H. Indo of Mitsui Engineering and Shipbuilding Ltd., Y. Ito and K. Kurumaji of Hitachi Ltd., and A. Kikuchi of Fuji Electric Co., Ltd.

I. Introduction

In 1974, a subcommittee was organized in Technical Research Association for Integrity of Structures at Elevated Temperatures (ISES) to investigate the structural behavior of high temperature components in HTGR, Hastelloy X, a nickel base superalloy, was selected in the investigation as one of the promising heat resistant alloys for HTGR. Steady and cylic creep tests with internal pressure together with other several tests, such as high temperature tensile tests and uniaxial creep tests, were performed by the working group of the subcommittee. Basic useful information obtained in the investigation for high temperature design have been published elsewhere [1,2].

In order to obtain more sufficient information for assessment of the high temperature strength of welded components with HTGR, steady and cyclic creep tests with internal pressure on circumferentially TIG welded cylinders were performed together with uniaxial creep tests on round bar specimens welded in the same condition. Comparison of date obtained by both types of creep tests is very useful for understanding the structural behavior of welded components in high temperature environment, and is especially necessary in case of on-site welding, where solution heat treatment is hardly applicable. Assessment of strength and reliability of welded components for high temperature use can be much assured by comparing the results of both types of creep tests.

2. Experimental Procedure

2.1 Material

The test cylinder made of Hastelloy X was fabricated by hot-extrusion and soaking treatment at 1,140°C for 15 minutes, and was finished to 75 mm in outer diameter and 11.5 mm in wall thickness. Chemical composition of the base metal of the test cylinder and the filler metals used in the conventional TIG welding are shown in Table 1. Grain size of the Hastelloy X of the test cylinder was of ASTM No. 5 to 7.

2.2 Specimen

The edge of the test cylinder was prepared for welding as shown in Fig. 1 (a). TIG welding was applied circumferentially on the grooved edge according to the welding sequence given in Fig. 1 (b). In order to study the behavior of the components as welded at an assembling site, the weld was not subjected to post-weld heat treatment. Configuration of the welded test cylinder is illustrated in Fig. 2.

Round bar specimens for uniaxial creep tests were taken from the welded cylinder, also from the non-welded cylinder for comparison. They were finished to 6 mm in diameter and 30 mm in length. The weld joint of the uniaxial specimen was situated in the middle of the length.

2.3 Test Apparatus

The test apparatus for the steady and cyclic creep tests of the cylinder with internal pressure is composed of an electric heater, an argon gas supply, a discharge line, pressure and temperature automatic control system and various measurement devices. The steady or cyclic internal pressure was produced by supplying pressurized argon gas inside the cylinder from a gas bomb which was regulated by an automatic pressure control valve. Deformation of the cylinder was detected during the test by six dial gauges mounted on quarts rods which was inserted into the electric heater through small holes and extended on the surface of the test cylinder.

2.4 Test Condition

The creep tests were performed at the temperatures 800, 900 and 1,000°C. The internal pressure applied to the cylinder ranged from 0.4 to 8.5 MPa according to the assigned test temperature and expected life time. The cyclic creep tests were performed for the purpose of finding out, if any, the effects of interrupted creep and creep fatigue interaction. The wave form of the applied internal pressure in the cyclic creep test was trapezoidal with short loading, unloading time and a long hold time of the applied pressure. The hold time was 10 minutes, 2 and 24 hours in each cycle.

3. Experimental Results

3.1 Creep Test with Internal Pressure

Figure 3 shows some typical creep curves which were obtained by the measurement of expansion at the middle section of the non-welded and welded test cylinders during the creep test with internal pressure. The full lines denote the results of non-welded cylinders and the dashed lines denote those of welded cylinders, that is, the creep curves of the weld metal located in the middle section of the welded cylinders. The non-welded cylinders crept via secondary and tertiary stages and failed finally after a large expansion, while the weld metal of the welded cylinders expanded almost linearly with time at a lower creep rate and failed before attaining the tertiary stage, thus the welded cylinders showed remarkably shorter creep life and much smaller rupture elongation compared with the non-welded cylinders.

Figure 4 shows the stress vs rupture time relation obtained in the same creep tests of the cylinders. The rupture time of the welded cylinders was much shorter than that of the non-welded cylinders compared at the same stress level, and difference between them was more remarkable in higher test temperatures. The effect of cyclic loading on the creep rupture behavior was not clear.

Figure 5 shows a typical example of deformation of a welded cylinder after creep failure with internal pressure. The diametral elongation of the base metal sections of the cylinder was 4 to 5%, while that of the weld metal section was only 1%. Thus the deformed shape of the welded cylinder became like an hour glass. All other TIG welded cylinders showed quite a similar feature with this example.

It was observed that many longitudinal fine cracks initiated around the weld metal sections before the failure, and a few of them grew faster and penetrated through the wall of the cylinder. The failure of the cylinder was defined as the stage when the pressurized gas inside the cylinder leaked through the penetrated cracks.

In Fig. 6 is shown a typical example of microstructure of the weld metal after the creep failure. The weld metal consists of extremely large austenite grains of dendrite structure which causes the creep rate of the welded section very low$^{3)}$. The failure seems to occur due to separation of the dendrite structure at primary grain boundaries. This feature suggests a reason why the weld metal yields such low ductility in the creep test.

3.2 Uniaxial Creep Test

Figure 7 shows the stress vs rupture time relation obtained by the uniaxial creep tests on round bar specimens with and without a TIG weld joint. In the welded specimens the creep failure occurred in the weld metal at 800 and 900°C, while it occurred in the base metal at 1000°C. This means that the creep rupture strength of the weld joint at 800 and 900°C was a little lower than that of the base metal and the rupture strengths of the weld metal and the base metal were almost equal at 1000°C. In any case, the difference of creep rupture strength in uniaxial specimens with and without a weld joint was very small as shown in Fig 7.

In contrast to the sufficient creep ductility of the base metal, the reduction of area of the weld metal section of the uniaxial specimen at failure was extremely low, that is 10% at 800°C, and 1 to 4% at 900°C. Although at 1000°C the creep failure occurred in the base metal and the weld metal did not fail, the reduction of area of the weld metal section at failure was less than 1%.

4. Discussion

4.1 Creep Ductility and Rupture Strength of Weld Metal

As stated above, in the uniaxial creep tests the difference of the creep rupture strength between non-welded and welded specimens was observed very small, especially at 1000°C the weld metal did not fail. On the other hand, in the creep tests with internal pressure on cylinders with and without a circumferential weld joint, the difference was found to be very striking, and the decrease of creep strength due to the weld joint was observed to be maximum at 1000°C. This contradiction gives a warning that in the design of welded components for high temperature service, the assessment of their creep strength and reliability based on data obtained merely by uniaxial creep tests might mislead us.

The different results obtained by the uniaxial creep tests and the internal pressure creep tests on cylinders may be attributed basically to the extremely low creep ductility of the weld metal. The following more detailed discussion may explain the reason:

(1) In case of the round bar specimen used in the uniaxial creep test, where the base metal and the weld metal are joined in series, the creep deformations of both parts are not much restricted by each other, so that both parts may creep independently. Thus, the creep life of the uniaxial specimen with a weld joint is determined by the property of either part which attains first the critical value of its rupture elongation. On the other hand, in case of the circumferentially welded cylinder, interaction of the creep behaviors of the base metal and the weld metal is much larger. In the present case, because the creep rate of the base metal is much higher than that of the weld metal, the creep of the weld metal section of the cylinder is enhanced by the faster expansion of the base metal section, and the weld metal attains its critical value of the rupture elongation and fails in much shorter time than its proper creep life. Thus, the creep life of the welded cylinder becomes much shorter than that of the non-welded cylinder.

(2) The uniaxial stress in the round bar specimen with a weld joint acts along the direction of growth of the dendrite structure of the weld metal, and the strength of the weld metal is maximum in this direction. On the other hand, the hoop stress, i.e. the maximum principal stress in the cylinder, due to internal pressure, acts crosswise to the growth direction of the structure. As the dendrite structure is weak and lacks of ductility crosswise to the growth direction, the stress is apt to tear the structure without much creep elongation.

4.2 Improvement of TIG Welding

As already mentioned, creep ductility of weld metal plays a very important role on the strength of welded components for high temperature use. According to the ASME Code, Case 1592, the allowable limit of membrance strain in weld metal is specified as 0.5%. The present test shows that the creep ductility at failure of the weld metal of the TIG welded cylinder with internal pressure is only 1 – 3% at 800 – 1000°C, when many cracks are found in it and leakage occurs. Accordingly, it may be reasonable to assume that before the allowable limit by the Code criterion is attained, cracks can possibly initiate in the weld metal of the cylinder which is welded by the conventional TIG welding procedure. Hence, it was considered in the subcommittee that further investigations for improving the weld metal and welding procedure were essentially necessary to actualize the use of Hastelloy X components.

In order to obtain better weld metals which can present sufficient ductility and creep rate comparable to those of the base metal, application of several filler metals, such as Hastelloy X added with 0.02% Zr. or with reduced silicon, Incoloy 800 and the modified-Hastelloy X, were attempted to the circumferential TIG welding of cylinders and creep tests on the welded cylinders with internal pressure were performed at the condition of temperature of 900°C and hoop stress of 33.3 MPa. Some improvements were found in the test cylinders TIG welded with Incoloy 800 and the modified-Hastelloy X as the filler metals. These two kinds of welded cylinders failed at 5 – 10% diametral creep elongation, whereas other test cylinders failed only at 2 – 3% diametral elongation, and their creep rate was higher than that of the former two kinds of cylinders.

The microstructures of these weld metals photographed after the creep failure are illustrated in Fig. 8. The weld metal with the modified-Hastelloy X filler metal seems to have failed by linking the voids developed along the grain boundaries, while that with Incoloy 800 filler metal which consists of some different phases seems to have failed by crack propagation, and the cracks which developed both from outer and inner surfaces of the cylinder seem to have stopped or changed their propagation route at the phase boundaries in the weld metal. These features of the microstructures suggest that the process of the creep failure in these weld metals is different from that mentioned before in the weld metal of the cylinder with conventional TIG welding.

Figure 9 shows a relation between the observed circumferential elongation at failure of the weld metal and the maximum value of elongation of the base metal of the same cylinder. The number beside the spot denotes the filler metal used in the weld. The relation may be put to be linear. The average value of circumferential elongation at rupture obtained by scores of non-welded Hastelloy X cylinders was about 40%. From Fig. 9, it is expected that creep failure of a welded cylinder may appear in the base metal section if the elongation of the weld metal at failure attains the value of 16% or more. Accordingly, one of the targets for improving the TIG welding of Hastelloy X cylinder should be put on the development of a weld metal which can yield circumferential elongation of 16% or more at failure, i.e. approximately a half value of the base metal. This ductility value is sufficient for satisfying the design limit criterion specified in ASME Code, Case 1592.

4.3 Electron Beam Welding

As another attempt to improve the welding, a procedure with electron beam welding (EBW) was applied to the circumferential welding of the Hastelloy X cylinder. Creep tests performed by the working group of the Subcommittee showed that EBW gave better results than the TIG welding as the test temperature increased, that is, the rupture strength of the welded cylinder with EBW was nearly equal to that of the conventional TIG welded cylinder at 800°C, then the former became higher than the latter, but still lower than that of the non-welded cylinder at 900°C, finally it became almost equal to that of the non-welded cylinder at 1000°C.

A picture of the welded cylinder with EBW which was deformed by a creep test at 900°C is shown in Fig. 10. The weld metal section located in the middle of the cylinder was sufficiently expanded just like the non-welded cylinder, so that the creep ductility of the weld metal of the cylinder with EBW was almost equal to that of the non-welded cylinder. Still, the failure of the cylinder with EBW took place in the weld metal section, where a few cracks grew and penetrated through the wall of the cylinder. Besides the main cracks, many fine cracks were found in the weld metal, and a lot of voids were observed to develop inside the structure of the base metal.

5. Conclusion

The present investigation, performing steady and cyclic creep tests with internal pressure on welded and non-welded Hastelloy X cylinders, leads to the following conclusion:

1) The creep rupture strength of the conventional TIG welded cylinders is much lower than that of the non-welded cylinders. Data obtained by uniaxial creep tests on specimens welded in the same condition can hardly give the basis of the assessment of rupture strength of the welded cylinders.

2) The reduction of creep strength of the welded cylinders is mainly due to the extremely low creep ductility of the weld metal. Cracks may possibly initiate in the weld metal of the cylinder, which is welded by the conventional TIG welding procedure, before the design strain limit of 0.5% is attained.

3) Improvement of the weld metal and the welding procedure is quite necessary in Hastelloy X components for high temperature use. Incoloy 800 and the modified-Hastelloy X gave a fairly good improvement as the filler metal. Further effort is needed to improve the filler metal so as to achieve a sufficient rupture elongation.

4) The weld metal of the cylinder welded with electron beam welding procedure showed a superior creep ductility and gave fairly good creep properties comparable to those of the non-welded cylinder.

References

(1) Udoguchi T., et al, "Steady and Cyclic Internal Pressure Creep Tests of Hastelloy X Tubular Specimens at 800 to 1000°C", ASME/CSME Conference of PVP, Montreal, June, 1978.

(2) Udoguchi T., et al, ISES Report No. 7709, 1977.

(3) Nakanishi T., et al, J. Japan Inst. Metals, Vol. 41, No. 3, 1977. 263.

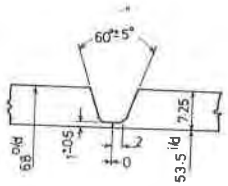
Table 1 Chemical Compositions of Hastelloy X cylinder and filler metals

	C	Mn	Si	P	S	Cr	Co	Mo	W	Fe	Ni	Al	Ti
cylinder	0.07	0.77	0.44	0.017	0.005	21.23	1.07	9.23	0.50	18.18	bal	0.15	0.01

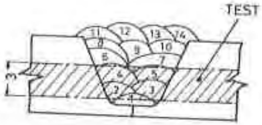
filler metal

standard HX	0.10	0.52	0.30	0.005	0.005	21.91	0.97	8.93	0.55	18.42	bal	-	-
Mod. HX*	0.09	0.75	0.22	0.009	0.002	21.47	1.60	8.80	0.50	17.97	bal	-	-
Incoloy 800*	0.04	0.55	0.30	0.005	0.005	21.00	-	-	-	bal	32.5	0.32	0.55
HX with 0.02% Zirconium*	0.09	0.49	0.67	0.005	0.005	21.88	1.52	9.01	0.53	17.91	bal	0.12	Zr 0.02
HX reduced Silicon*	0.05	0.55	0.008	0.005	0.006	21.99	1.46	8.78	0.53	18.58	bal	0.12	-

* used for improvement of creep property.



(a) Edge preparation



NO. OF PASS	WELDING CURRENT(A)
1 ~ 5	65
6 ~ 10	75
11 ~ 14	70

(b) Welding sequence

DIA. OF FILLER METAL : 1.2 MM
SHIELD GAS : ARGON 10 L/MIN.
BACK SHIELD GAS : ARGON 5L/MIN.
INTER PASS TEMP. : BELOW 100°C

Fig. 1 Welding procedure of Hastelloy X cylinder joint.

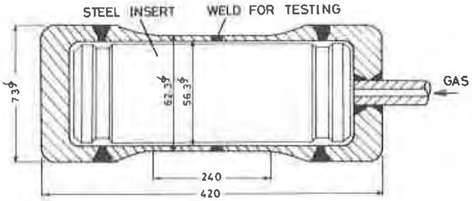


Fig.2 Structure and dimension of welded cylindrical specimen for creep testing with internal pressure loading.

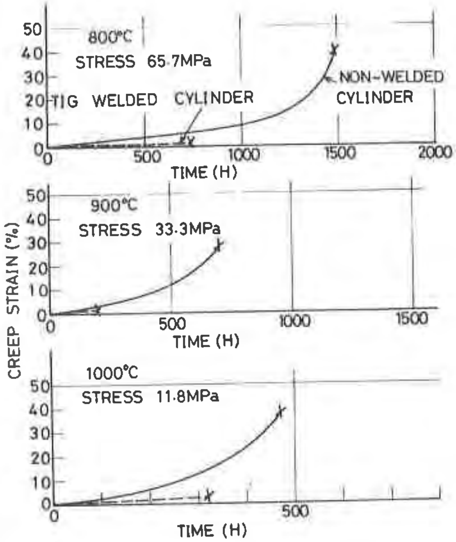
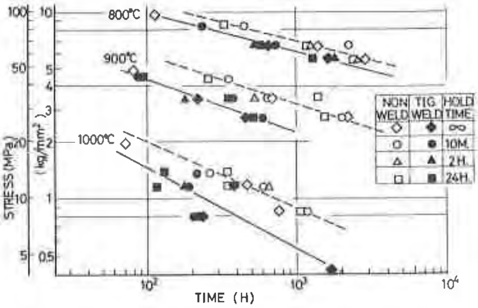


Fig.3 Typical creep curves at the centre of cylindrical specimens



Fi.4 Creep rupture time vs stress of cylindrical specimens subjected to creep testing with internal pressure loading.

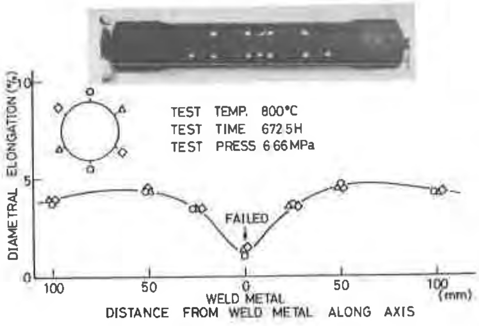


Fig.5 Expansion of the welded cylinder after creep testing with internal pressure loading.

Fig.6 Microstructure of TIG weld metal after creep testing with internal pressure of 3.36MPa, at 900°C and for 85 hours.

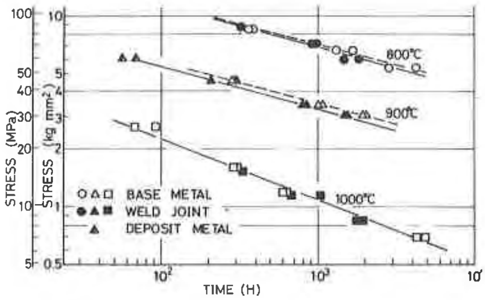
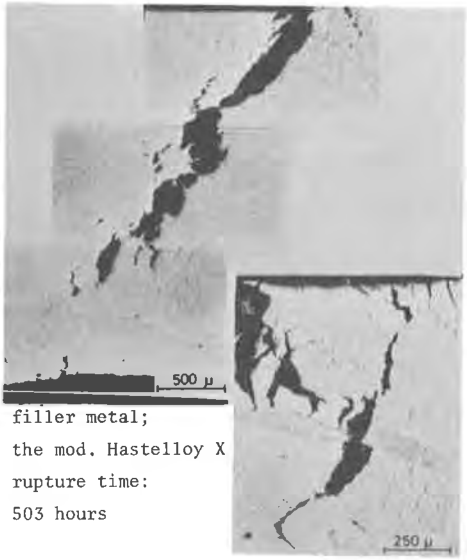


Fig.7 Creep rupture time vs stress of base metal and TIG welded joint obtained from uniaxial creep testing.



(a) filler metal;
the mod. Hastelloy X
rupture time:
503 hours

(b) filler metal; Incoloy 800
rupture time: 617 hours

Fig.8 Microstructure of TIG weld metal using the modified Hastelloy X and Incoloy 800 as filler metal after creep testing with internal pressure of 3.33MPa at 900°C.

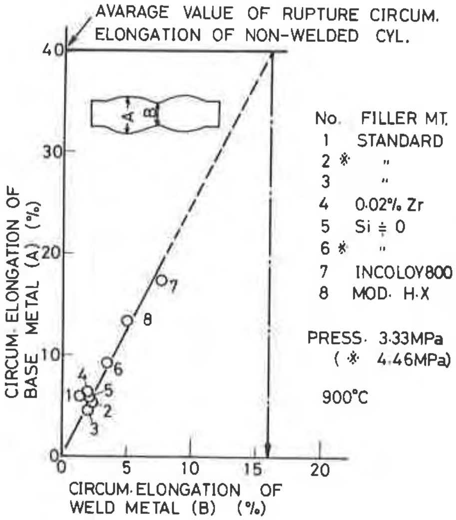


Fig.9 Circumferential elongation of weld metal vs that of base metal.

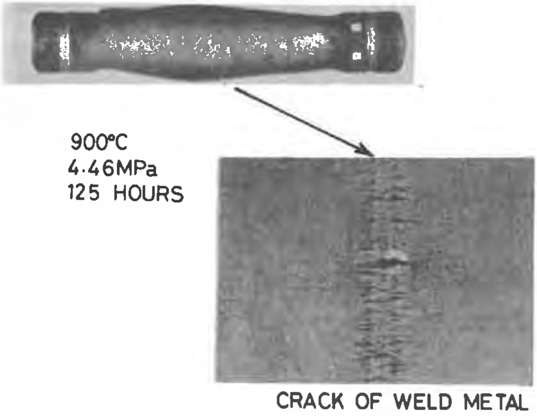


Fig. 10 Deformation of the electron-beam welded cylinder after creep testing with internal pressure loading.