Company name	Kansai EPCO
Date of occurrence	25.September.2007
Unit name	Mihama 2
Event	Flaws Found in Steam Generator A Reactor Coolant Inlet Nozzle Weld
International Nuclear Event Scale (INES)	0
Status of report	Final report

Status when event occurred

During the 24th planned outage, considering the stress corrosion cracking events in domestic and foreign plants, shot-peening (*1) work to reduce residual stress in the surface of the steam generator (hereafter referred to as “S/G”) reactor coolant inlet and outlet nozzle welds (total four welds) where 600 series Ni base alloy had been used was to be performed as a preventive maintenance task. To check the surface conditions of the nozzle weld portions prior to the work, eddy current test(*2) (hereafter referred to as the “ECT”) was performed for the S/G nozzle weld portion surfaces and significant indications were identified for 13 locations on the inlet nozzle weld portion of S/G-A. Also, visual checking of these locations having significant signals was performed and a flaw was identified at one location. For the outlet nozzle of S/G-A and the inlet and outlet nozzles of S/G-B, no significant signal was identified.
Further, for the locations found with significant ECT indication, a penetrant test (hereafter referred to as “PT”) was performed and as a result significant penetration indicating patterns (maximum length: approx. 17 mm) were identified. In addition an ultrasonic test (hereafter referred to as “UT”) was performed and thereby the maximum flaw depth was evaluated at approx. 13 mm (for the location of the maximum length), resulting in the residual thickness of the affected location (approx. 68 mm) evaluated to be below the thickness described (75 mm) in the application for construction permit based on the Electricity Utilities Industry Law.

*1: Shot-peening
A technique to reduce residual stress in a weld portion surface by peening the weld portion surface with shot which consists of small metal balls.
*2: Eddy current test (ECT)
A technique to detect a flaw in a test subject using an electromagnetic induction change caused in a material while eddy currents being made in the material.
*3: Penetrant test (PT)
A technique to observe a flaw as a penetrant indication pattern developed with a developer agent. In this process to make a flaw opening on the test subject surface easy to check visually, a highly permeable liquid including visible dye is used to penetrate the flaw, then the excess liquid is removed and the developer is applied.
*4: Ultrasonic test (UT)
A technique to detect defects inside a material using ultrasonic wave which then propagates in the material and reflects any material discontinuity such as a defect.

Summary of examination of cause

(1) Observation results by SUMP(*5) and etching(*6)

[Weld portion]

Among the 13 locations found with significant signal indication for the S/G-A inlet nozzle, the No.4 location of indication which was in the weld portion and evaluated to have the maximum depth was observed for its metal texture by means of SUMP and etching, and the result was as follows:

- The cracking was found in the circumferential weld and battering portion, but not reaching the safe end and the stainless overlay portion. The cracking was an associate of multiple cracking having approx. 3~5 mm length in the axial direction, and the overall length was approx. 17 mm with the maximum opening width of approx. 30 μm.
- The cracking was along the boundary of dendrite (column like shaped crystal made in melted metal while being cooled).
- In the buttering portion, three layers of weld metal were identified. Also in the circumferential weld two beads of TIG weld metal were identified. Any clear trace of rewelding was not found in the buttering portion and the weld portion.
- Any ductile cracking, fatigue cracking or corrosion was not found. Also it was verified that the flaw was not caused from a weld defect such as blow hole etc.

[Safe end]

Among the 13 locations found with significant signal indication for the S/G-A inlet nozzle, the No.13 indication found in the safe end was observed for its metal texture by SUMP and etching, and cracking in the safe end (SUS316 base metal) was identified at approx. 3 mm from the boundary with the circumferential weld. This cracking was multiple cracks with branching along the grain boundaries.

*5: SUMP

Film is adhered on failure portion surface in order to transfer the surface shape, and this is observed by microscope. By this, investigation of metal texture of the failure portion becomes possible, as well as by cutting out of metal sample.

*6: Etching

A method of metal texture observation by optical microscope in which the object test metal surface is polished and corroded using oxalic acid solution etc, through this process, the surface layer affected by polishing process is removed, and the texture to be observed is revealed.

(2) Investigation by cutting

[Weld portion]

a. Appearance observation

Appearance observation and replica observation of the cracking was performed and the result was as follows:

- Cracking No.4 consisted of multiple longitudinal cracks on the surface with an overall length of approx. 17 mm. The cracking did not reach the stainless overlay. Because the area around the cracking No.4

had been buffed prior to SUMP in the field, the surface was in a state polished to that of a mirror surface.

- Cracking No.6 consisted of two fine longitudinal cracks having surface lengths of approx. 2.5 mm and approx. 2 mm. In addition, in the area nearby the cracking No.6, equally spaced circumferential traces of machining having approx. 0.4 mm width were identified.
- Cracking No.10 consisted of two longitudinal fine cracks having a surface length of approx. 2.6 mm and approx. 2.0 mm. Because the area around the cracking No.10 had been buffed for SUMP of other cracking, the surface was in a state polished to that of a mirror surface.
- Cracking No.21 consisted of two fine longitudinal cracks having surface lengths of approx. 2.6 mm and approx. 1.3 mm. In addition, in the area nearby the cracking No.21, equally spaced circumferential traces of machining having approx. 0.4 mm width were identified.
- Also in the general portion of the weld metal, equally spaced circumferential machining traces of approx. 0.4 mm were identified.
- Any trace of rewelding or buffing during manufacturing was not identified for the cracking portion as well as the general portion.

b. Fracture observation

After opening the cracks, fracture appearance observation, SEM (scanning electron microscopy) observation, and cross-sectional microscopic observation were performed and the result was as follows. Though, since buffing for cracking No.4 was performed before SUMP in the field, the status of the fracture in the most outer surface layer could not be verified.

- Cracking No.4 consisted of multiple cracks of approx. 17 mm overall length on the surface, had the maximum depth of approx. 11.5 mm, which crossed most of the buttering portion and the circumferential weld portion, and propagated along the dendrite boundary. However, it did not reach the low alloy steel and the stainless overlay portion. For the safe end (SUS316 base metal) side, verification was not possible because of the notch introduced to open the fracture. As a result of SEM observation, fracture along the dendrite boundary was observed in the buttering portion and the circumferential weld portion.
- Cracking No.6 consisted of two cracks, one having approx. 2.5 mm surface length with approx. 3 mm maximum depth, and one having approx. 2 mm surface length with approx. 2.5 mm maximum depth, and developed along the dendrite boundary in the circumferential weld. However, it did not develop to the safe end (SUS316 base metal) side. As a result of SEM observation, fracture along dendrite boundary in the circumferential weld similar to the case of No.4 was identified.
- For cracking No.10 and No.21, because of difficulty in forced opening, cross-sectional microscopic observation for multiple cross-sections was performed. As a result, fractures were identified to have the maximum depth of approx. 1.8 mm and approx. 0.47 mm respectively, and to have developed along the dendrite boundary.
- As a result of cross-sectional microscopic observation, deformed texture considered to be due to machining effect was identified in the most outer surface layer of the weld (general portion).

c. Analysis of surface deposit

Main elements were the components of the weld metal (Ni, Cr, Fe etc.) and harmful elements such as chlorine were not found.

d. Measurement of residual stress

By X-ray the residual stress measuring method, the residual stress was measured for the surface layer of the buttering and the weld portion. As a result, the residual tensile stress in the buttering portion was approx. 280 MPa (circumferential) and approx. 73 MPa (longitudinal), while the circumferential weld was approx. 482 MPa (circumferential) and approx. 346 MPa (longitudinal).

e. Hardness measurement

As a result of hardness measurement, in the surface layer with approx. 0.1 mm depth, increased hardness was identified (circumferential weld: Max. approx. 400 Hv, buttering: Max. approx. 470 Hv). This was considered to be due to machining effect.

f. Chemical composition analysis

For the circumferential weld and the buttering portion as well, the composition was equivalent to that in the mill sheets.

[Safe end]

a. Appearance observation and PT

Appearance observation and replica observation were performed for the cracking and the result was as follows:

・ Cracking No.13 mainly consisted of two cracks having surface length of approx. 3 mm and of approx. 4 mm, respectively, in longitudinal direction and in circumferential direction. Because the area around the cracking No.13 had been buffed prior to SUMP in the field, the surface was in a state polished to that of a mirror surface.
・ Cracking 27 consisted of multiple cracks in longitudinal or circumferential direction with an overall surface length of approx. 3 mm. The area around the crack No.27 was in a state polished to that of a mirror surface as the case of the crack No. 13.
・ The cracks in the safe end were all found in a region of 3~7 mm from the weld portion and no cracking was found in other regions.
・ Equally spaced circumferential machining traces were identified.
・ Any trace of rewelding or buffing during manufacturing was not identified for the cracking portion as well as the general portion.

b. Fracture observation

After opening the cracks, fracture appearance observation, SEM (scanning electron microscopy) observation, and cross-sectional microscopic observation were performed and the result was as follows. Although, there was buffing performed before SUMP in the field, the conditions of the most outer surface layer of the fracture could not be verified.

・ Cracking No.13 mainly consisted of two fine cracks. One with approx. 17 mm surface length had the maximum depth of approx. 0.9 mm, and the other with approx. 4 mm surface length had the maximum depth of approx. 0.7 mm. Further as a result of the fracture SEM observation, fracture along the austenite grain boundary(*7) was identified.

・ Cracking No.27 was of approx. 3 mm surface length with the maximum depth of approx. 0.3 mm. Further as a result of the fracture SEM observation, fracture along the austenite grain boundary as the case of cracking No.13 was identified.

・ As a result of the cross-sectional microscopic observation, deformed texture and sliding lines thought to be affected by machining were identified in the general portion of the sefe end.

*7: Austenite grain boundary

This refers to a boundary between crystal grains having a honeycomb like shape, which is seen for austenite stainless steel represented by SUS316.

c. Analysis of surface deposit

Main elements were the components of the base metal of the safe end (Ni, Cr, Fe etc.) and harmful elements such as chlorine were not found.

d. Measurement of residual stress

By X-ray residual stress measuring method, the residual stress of the safe end was measured for the surface layer within 0.2 mm. As a result, the residual stress in the surface layer was approx. 571 MPa (circumferential) and approx. 356 MPa (longitudinal), while the residual stress in the region deeper than 0.1 mm was of compression.

e. Hardness measurement

As a result of the hardness measurement, the surface layer (within approx. 0.02 mm depth) had an increased hardness of the maximum 450 Hv compared with the inside (approx. 250 Hv). Further, the region found with significant hardness increase was approx. 0.1 mm depth of the surface, as the case of the weld portion.

f. Chemical composition analysis

The composition was equivalent to that in the mill sheets.

g. Measurement of sensitization degree

For the safe end (SUS316 base metal), sensitization degree measurement in the general portion, near cracking No.13 and near cracking No.27 was performed by EPR (Electrochemical potentiokinetic reactivation) analysis. As a result, the EPR values were below the detectable limit and no symptom of sensitization was identified. Also, from the result of TEM (transmission electron microscopy)/ EDS analysis, symptoms of sensitization (reduction in Cr concentration) were not identified.

(3) Investigation result of manufacturing and operation history

a. Investigation of manufacturing history

The affected S/G was manufactured during October 1991~February 1994, and installed during February 1994~March 1994. Through the records of work and inspection at that period and through the hearing from the relevant persons, the manufacturing history was investigated.

As a result, any singularity in the manufacturing procedure of the affected nozzle, the welder had enough experience, and thus reweld was not considered to have been performed based on the records and the hearing. Further, the hearing was performed from the workers in that period because the inner surface was machined after welding the safe end and so machining conditions might be somehow different depending on the worker. As a result, no singularity was identified and so the machining was considered to be done normally. Whether buffing after surface machining was performed or not was unable to be verified.

b. Investigation of operational history

The welding of the affected portion was performed during the S/G replacement work at the 14th planned outage (paralleled on September 26, 1994) and so the operational history through the 24th planned outage (off line on July 20, 2007) was investigated. The result was as follows:

1) Reactor coolant temperature and pressure

The events which occurred during that period that were accompanied with transients were not identified except for two events of reactor manual shutdown, one event of reactor automatic shutdown, and two events of power suppression. Also it was confirmed that these events including the transients did not show any abnormal temperature and pressure change (for the period of September 1994~ March 1998, confirmed based on the operation log).

2) Control of water chemistry

It was confirmed that the water chemistry in that period satisfied the plant’s safety preservation rules and harmful elements such as chlorine was controlled.

(4) Mockup test of machining

After welding the safe end, machining of the inner surface was performed. This could be a cause of increased hardness and high residual stress and therefore a mockup test was performed. The mockup test subject was an actual size cylinder of SUS316L of which the inner surface was padded by circumferential buildup welding of 600 series Ni base alloy. After it was machined with the condition based on the hearing result, observation of surface condition, hardness measurement and residual stress measurement were performed.

a. Observation of surface condition

On the surface after machining, equally spaced circumferential machining traces by a bit similar to ones seen for the actual case were verified. Further, it was confirmed that the machining traces disappeared when a simple buffing was performed.

b. Hardness measurement

[Weld portion]

The hardness of the surface was approx. 300~400 Hv or so, showing hardness increase compared with the initial hardness of 180 Hv. These results were of the same order as the measured value (368 Hv) for the actual safe end portion.

[Safe end portion]

The hardness of the surface was approx. 280~430 Hv, showing hardness increase compared with the initial hardness of 240 Hv. These results were of the same order as the measured value (395 Hv) for the actual weld portion.

c. Measurement of residual stress

[Weld portion]

Residual stress in the weld portion surface was approx. 600 MPa (circumferential) and approx. 580 MPa (longitudinal) as the maximum.

Further, when a standard buffing was performed, the residual stress became compressive (circumferential: approx. -153 MPa, longitudinal: approx. -428 MPa).

[Safe end portion]

Residual stress in the surface of was approx. 310 MPa (circumferential) and 360 MPa (longitudinal) as the maximum.

Further, when a standard buffing was performed, the residual stress shifted toward compression (circumferential: approx. 4 MPa, longitudinal: approx. -226 MPa).

(5) Investigation of literature

As a result of literature research on cracking in 600 series Ni base alloy welds, it was identified that as the events with damage in a similar portion of the reactor vessel outlet nozzle weld an event of leakage at V.C. Summer in the US (found in October 2000) and an event of UT indication at Ringhals 3 and 4 in Sweden (found in August 2000, and in September 2000, respectively) were reported. Also as a case of the pressurizer nozzle, an event of leakage at Tsuruga 2 (leakage from pressurizer relief valve nozzle and UT indication in safety valve nozzle, found in September 2003) was reported. These crackings were all circumferential, and in cases of V.C. Summer and Tsuruga 2, cracking developed through the weld metal and stopped at the boundary with low alloy steel and at the boundary with a safe end. The causes of these were all considered to be stress corrosion cracking (hereafter referred to as “PWSCC”) caused by high residual stress due to performance of rewelding.

Further, regarding PWSCC in 600 series Ni base alloy weld, a 360 °C temperature accelerated SCC constant load test was performed and it was concluded that PWSCC occurs at a stress greater than 300 MPa.

[Safe end portion]

As a result of the literature research on cracking in the safe end portion (SUS316 base metal), it was identified that the possibility of SCC occurrence is considered small even for a case of sensitized stainless steel because the PWR primary water chemical environment is controlled with a low concentration limit for dissolved oxygen and chloride ion.

On the other hand, for the BWR plant’s shroud and recirculation piping, generation of transgranular cracking in the machined surface layer caused by welding and machining, and as a result of it, generation and development of interglanular cracking were reported.

For cold worked non-sensitized stainless steel, studies on SCC generation and development under PWR environment is progressing and generation of SCC presently has not been verified. However, regarding the development of SCC, it has been known from the test result with a CT coupon (given precracking) that the development rate increases with hardness. From this, cold worked non-sensitized stainless steel is considered to have a susceptibility to SCC under a PWR environment. Further, the development rate is evaluated to be lower under a low oxygen concentration environment (equivalent to PWR environment) than under a high oxygen concentration environment (equivalent to BWR environment).

(6) Other forms of damage

Also investigation for the possibility of ductile cracking, fatigue cracking, and corrosion was performed. However, there was no anomaly in the usage environment and used materials and thus these are not considered to be the cause.

Also scratches made during manufacturing or periodic tests were not considered to be the cause based on the records and actual plant investigation result. Further, regarding welding deficiency and defect in weld during manufacturing, nothing to be the cause was found from the records and actual plant investigation results.

(7) Summery of the investigation results

[Weld portion]

・It was verified that the cracking in the 600 series Ni base alloy weld portion was intergranular cracking along the dendrite boundary and exhibited PWSCC aspects.
・On the inner surface of the 600 series Ni base alloy weld portion, trace of machining during manufacturing was identified, and residual stress exceeding the threshold value for PWSCC generation of approx. 300MPa was identified.
・It was confirmed that there was no rewelding during manufacturing, there was no singularity found in the manufacturing history and operational history, and there were no harmful elements.

[Safe end portion]

・Cracking in the safe end portion (SUS316 base metal) was very minor intergranular cracking and found only nearby the weld portion boundary. (The initiation point of cracking generation was not able to be identified.)
・In the depth range of 0.1 mm from the inner surface, a remarkable increase in hardness thought to be an effect due to machining and high residual tensile stress were identified.
・It was confirmed that there was no rewelding during manufacturing, there was no singularity found in the manufacturing history and operational history, and there were no harmful elements.

Cause of event

[Weld portion]

Though the initiation point of cracking was not identified, it is presumed that during manufacturing of the replacement S/G, the machining of the 600 series Ni base alloy weld portion was performed, thereby high residual stress was caused in a very thin surface layer on the inner surface, and this high stress caused PWCSS. Further, the generated cracking is considered to have developed due to stress etc. during operation.

[Safe end portion]

During manufacturing of replacement of the S/G, after welding the inlet nozzle and the safe end using 600 series Ni base alloy weld metal, machining was performed, and thereby a hardness increase and a high residual stress in a very thin surface layer on the inner surface nearby the safe end weld were caused.

Although the cracking initiation point was not identified, intergranular cracking nearby the weld is considered to have developed due to stress during operation etc.

Measures to prevent recurrence

[Weld portion]

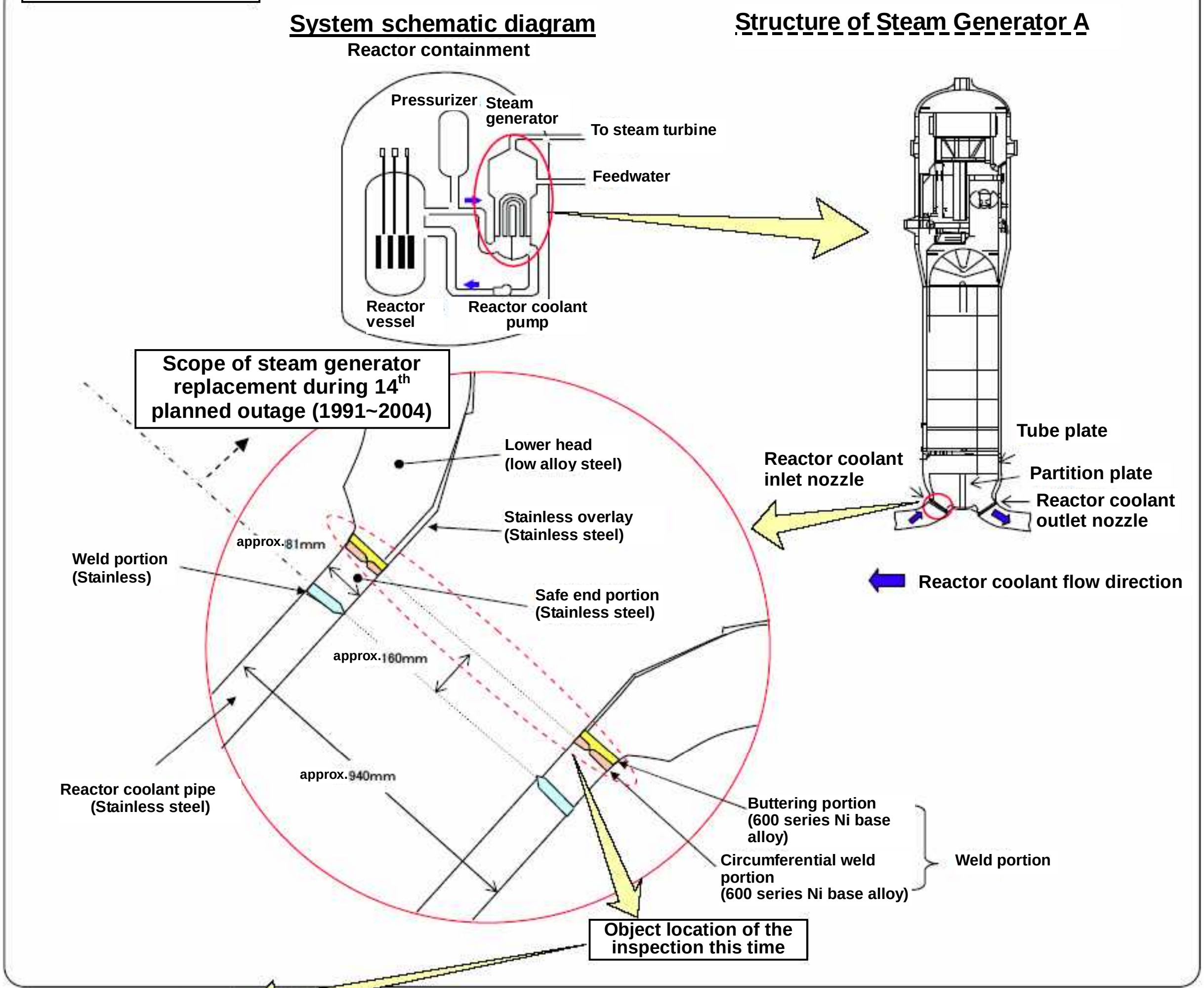
The portion cut out will be recovered using 690 series Ni base alloy weld which has better corrosion resistivity. In addition, for caution’s sake, a buffing finish will be applied in order to reduce residual stress in the affected portion.

[Safe end portion]

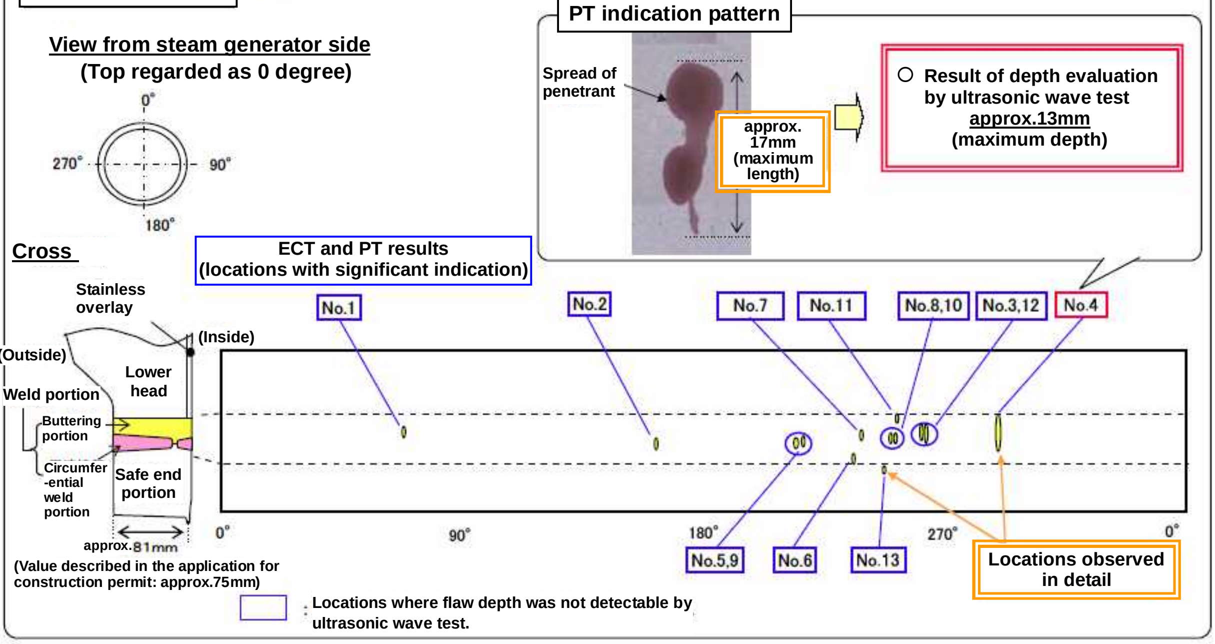
The safe end portion (SUS316 base metal) will be replaced with a new one and finished with buffing. Further, a study on cracking generation in the safe end will be performed to enhance relevant knowledge.

Status of Mihama Unit 2 planned outage
(Cause and Countermeasures of the Flaw in Steam Generator A Reactor Coolant Inlet Nozzle Weld portion)

Location of flaw



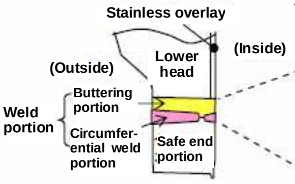
Inspection results



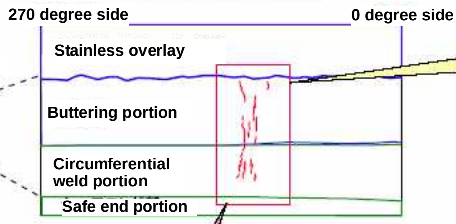
Observation results for the weld portion

- ○ Multiple cracks of approx. 3 to 5 mm length existed intermittently in longitudinal direction.
- ○ Cracking was along dendrite boundary in the weld portion.

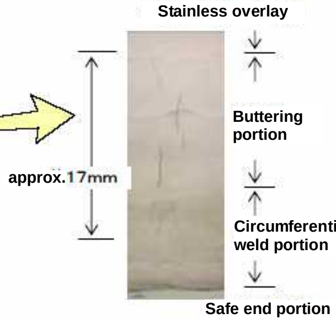
Cross



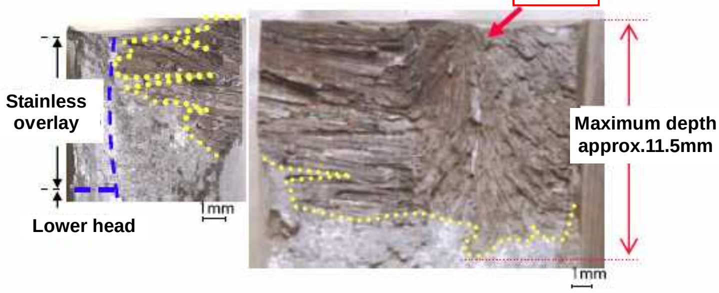
Etching observation result for No.4 (location with the maximum depth)



SUMP observation results



Fracture observation



- ○ Maximum depth of approx. 11.5 mm, developing along dendrite boundary.

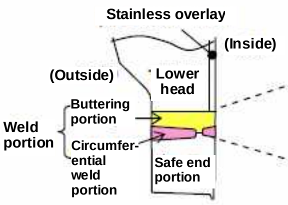
Replica observation result of weld portion

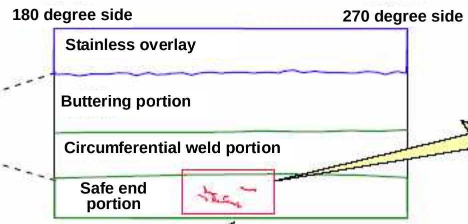
- ○ Trace of machining was found.

Safe end observation result

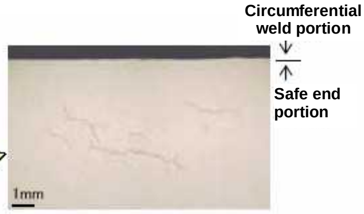
- ○ Multiple cracking was found with branching along grain boundary of metal crystal.

Etching observation result for No.13

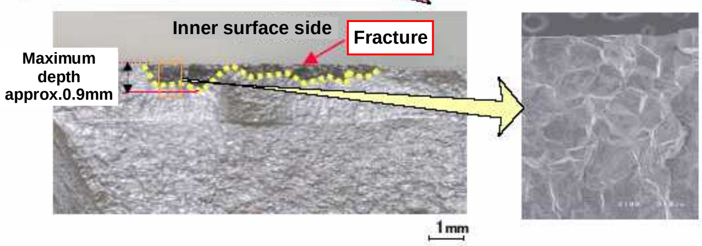




SUMP observation results



Fracture observation



- ○ Maximum depth was approx. 0.9 mm, developing along austenite crystal grain boundary.

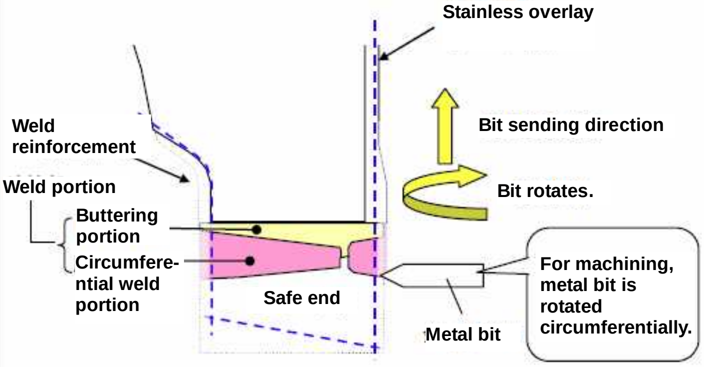
Replica observation result of safe end

- ○ Trace of machining was found.

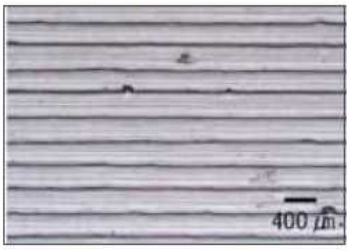
Machining

[Machining during manufacturing]

- - - : Area machined with machining apparatus to remove raggedness of the inner surface due to welding etc.



Machining trace resulted by reproducibility test

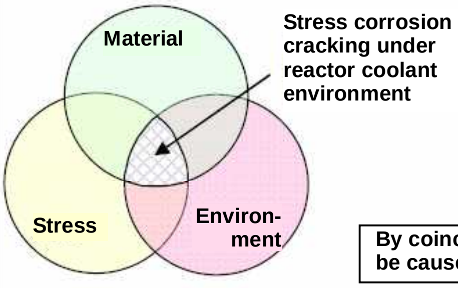


○ Machining trace similar to that of replica of the actual portion was seen.

○ Residual stress measurement result
Large circumferential tensile residual stress was identified.

Presumed cause

Weld portion



- Environment: High temperature reactor coolant water chemistry environment
- Material: 600 series Ni base alloy susceptible to stress corrosion cracking
- Stress: Tensile residual stress due to welding and machining

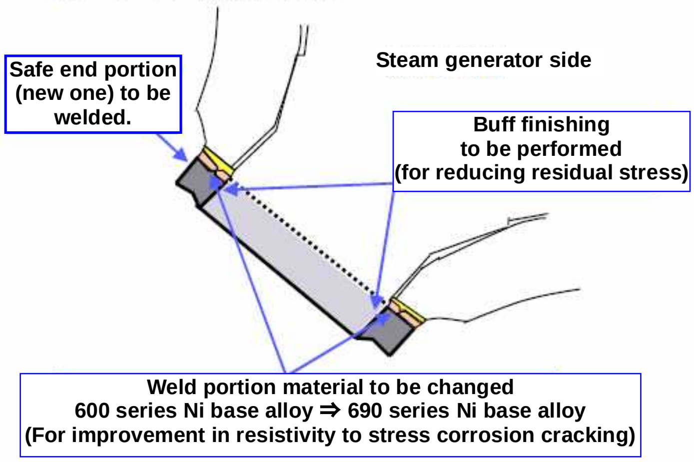
By coincidence of the three factors, stress corrosion cracking was presumed to be caused under reactor coolant environment.

Safe end portion

○ High tensile residual stress was caused in very thin surface layer of inner surface. Nearby the weld portion, cracking was presumed to have developed along austenite crystalline boundary due to stress during operation etc.

Countermeasures

[New safe end to be welded]



[Pipe (elbow) portion to be replaced]