Failures of Fastening Screws and Their Preventive Methods

Environmental failure of bolts, 4th report (the last half)

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1. Introduction

In the previous report (the first half), two kinds of the fatigue failure of bolts have been described in the corrosive environment. In addition, failure cases by delayed fracture of bolt are introduced with referring to the mechanism of delayed fracture. Though fatigue failure of bolts occurs, regardless of steel grade, shape, etc. under repeated applications of some kind of stress, environmental failure is limited to high-tensile bolts which are very sensitive to corrosive environment in the case of delayed fracture. This report introduces another example of environmental failure of bolts. That is called stress corrosion crack (SCC), which is a little bit different from the former bolt failures[(1)-(4)].

2. Failure of fastening bolt for the level gauge of an Ar-gas holder[(1)-(3)]

2.1 Outline of failure

Excessive leakage of Ar gas was detected from the rear side of the level gauge for an Ar-gas holder. On inspection, it was found that the fastening bolts of the level gauge were broken. Since many gauges of the same type were in use, the broken bolt was closely investigated to prevent recurrence of the same trouble. The gauge had been in service for 6 years and 10 months. Bolt details are SUS630 (H900), 1/4-20UNC, unified thread, outside diameter:φ6.35mm, root diameter:φ4.976mm, pitch:1.27 mm, thread length: 25.4 mm, overall underhead length: 63.5 mm, tightening torque: 2 kgf-m. An axial tension of 317 kgf is produced when the gas pressure is 70 kgf/cm^2 (see Fig.4.1).

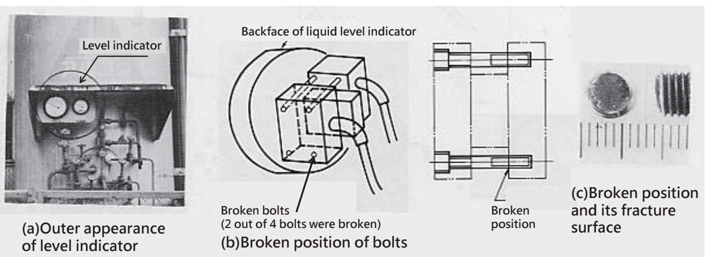

Fig. 4.1 Outer appearance of equipment and broken position

2.2 Items investigated

(1) Analysis of chemical composition and observation of the structure by an optical microscope.

(2) Inspection of appearance.

(3) Mechanical properties (hardness distribution).

(4) Observation of fracture surface and analysis of elements in the fracture surface.

2.3 Results of investigation and discussion

(1) Bolt material

Table 4.1 lists the chemical composition and mechanical properties of the bolt. The Cu and Nb content deviate from the JIS standard for SUS630.

Table 4.1 Chemical composition and mechanical properties of broken bolt

	Chemical composition [mass,%]									Mechanical properties	
	C	Si	Mn	P	S	Ni	Cr	Cu	Nb	P. S [kgf / mm^2]	T. S [kgf / mm^2]
Broken bolt	0.07	0.38	0.35	0.021	0.015	4.58	15.46	2.24	0.07	–	(150~160)*
SUS630 Spec.	≦0.07	≦1.00	≦1.00	≦0.040	≦0.030	3.00/ 5.00	15.50/ 17.50	3.00/ 5.00	0.15/ 0.45	≧120	≧134

* Converted value from Vickers hardness number, PS: proof stress, TS: tensile stress, Spec.: specification

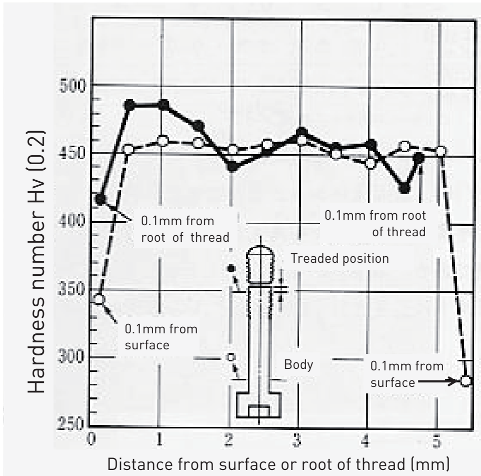

Fig.4.2 Hardness distribution of body threaded portion

The hardness distribution is shown in Fig.4.2. Though a noticeable difference in hardness distribution is observed between the vicinity of the broken point and the body, the hardness of the whole bolt is very high.

The optical micrograph is shown in Fig.4.3. The microscopic structure shows a tempered martensitic structure. Therefore, the tempering temperature is considerably low.

(2) Observation of fracture surface and analysis of elements in the fracture surface

It will be noted from Figs.4.4 and 4.5 that a large proportion of the fracture surfaces is the intergranular fracture surface. The final fracture is a ductile fracture. The existence of Cl and S was detected when part of the fracture surface was analyzed (see Fig.4.6). Corrosion pits were locally observed at the thread root and body of the bolt (see Fig.4.7).

(3) Tightening force of bolt

Assuming that the tightening torque of the bolt is 2kgf-m, the axial tension during service, 317 kgf, and the torque coefficient, 0.15. The stress to be created in the transverse section at the root under the above conditions is 123 kgf/mm^2. In general, the axial force for tightening a high-tension bolt is 75% of the standard yield point, and therefore the axial tension for tightening this bolt is 105 kgf/mm^2. It may be said that this tension is quite large. In cases where the tensile strength of a bolt is very high (about 150~160kgf/mm^2) and the axial tension for tightening is large as described above, the bolt becomes sensitive to the influence of the environment and is apt to fracture in a brittle fashion (see Fig.4.5).

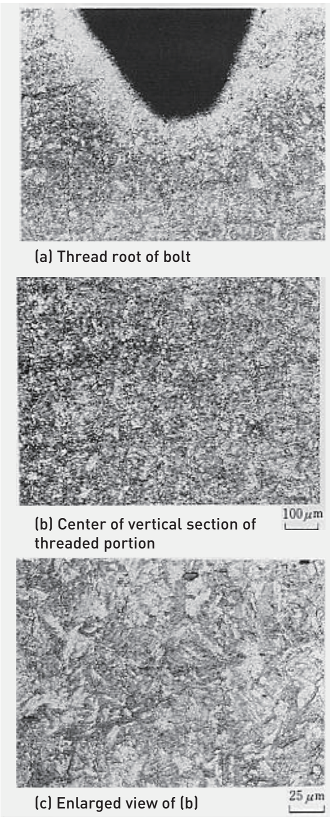

Fig. 4.3 Microstructure of broken bolt

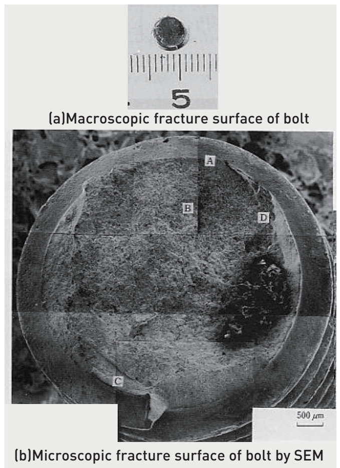

Fig.4.4 Observation result of fracture surface

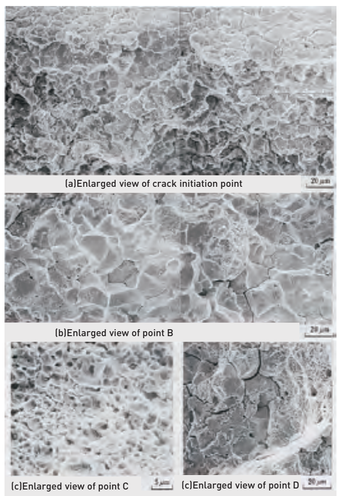

Fig.4.5 Observation results of fracture surface by SEM (ref. Fig.4.4)

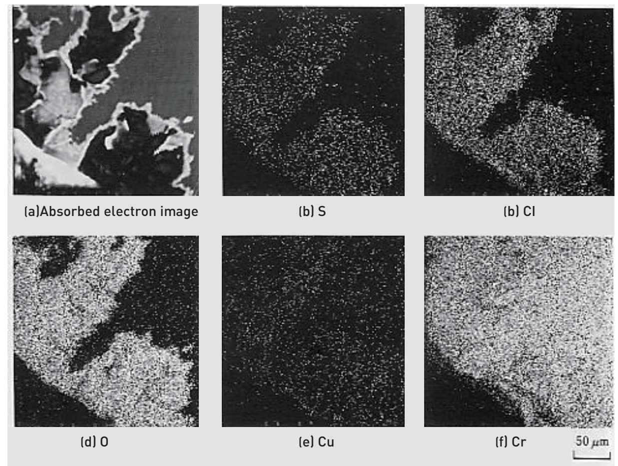

Fig.4.6 Chemical analysis of fracture surface

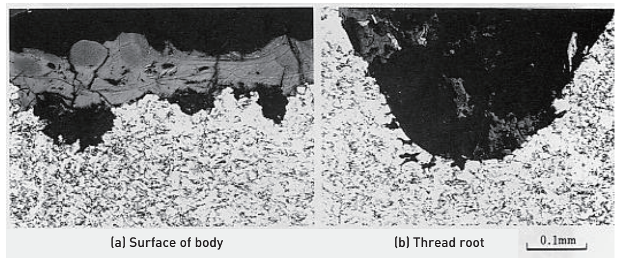

Fig.4.7 Microstructure in vertical section of bolt

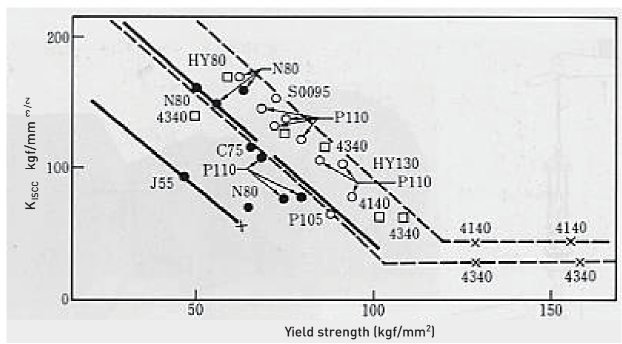

Fig.4.8 Effect of yield strength on KISCC in H_2S

(4) Summary

Summarizing the results of the investigation described above, it is judged that the so-called stress corrosion cracking resulted from pitting caused in the high-tension bolt which was tightening under a large tightening axial force. To prevent this cracking, it will be effective to decrease the strength of the bolt by changing the heat-treating condition from H900 to H1075 and to decrease the bolt-tightening torque from 2 kgf-m to 1 kgf-m. In addition, Fig.4.8 shows the effect of yield strength on KISCC in H2S and will introduce the more adequate material against stress corrosion crack.

3. Failure of stud bolts for the heating furnace[4]

The insulating materials are recently used in the heating furnace instead of fire brick in the view point of saving energy, decreasing weight, shortening of construction period and reduction in cost. As the temperature in the furnace is extremely high, the stud bolt fastening the insulating materials is applied with austenitic stainless steels (mostly SUS304). The mass failures of the stud bolts made of SUS304 has happened about the heating furnace for steel blooms. The broken stud bolts have been investigated for preventing the similar failures in the future and accounting for increase of application to insulating materials to the heating furnace.

3.1 Outline of failure

The heating furnace for steel blooms is composed of a pre-heating zone, heating zone and soaking zone from the charging side with atmospheric temperature between 600 and 1300℃. The stud bolts are broken in the pre-heating zone (600~800℃), i.e. in the relatively low temperature. Figure 4.9 shows the schematic illustration of stud bolt fastened. As shown in this figure, the stud bolt is welded by resistance welding with steel plate (SS400, thickness in 4.5mm) in

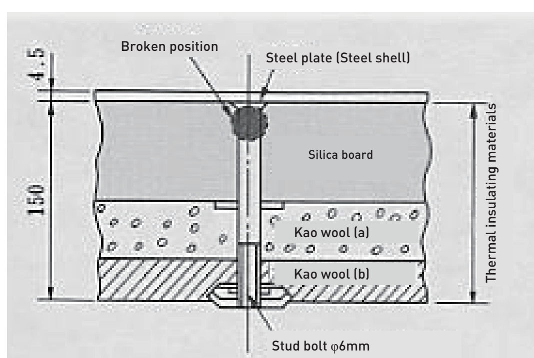

Fig.4.9 Schematic illustration of fastened stud bolt

the ceiling with 2m in height from the furnace bottom oriented with skid pipes. The insulating materials are made of three layers with silica board, Kao wool (a) and Kao wool (b) from the steel plate side. The several hundreds of SUS304 stud bolts are broken and the insulating materials of $20m^2$ (in area) fell down after three years since operation. In addition, the steel plate was over 60℃ in temperature and the theoretical dew point of fuel gas is 58℃. When the temperature of furnace decreases, there is possibility that the dewing happens among the steel plate, the bolts and the insulating materials.

The cooling seawater leaked from the skid pipes in the above heating furnace since 6 months of operation. The leakage of seawater appeared in 2 parts of skid pipes between pre-heating zone and heating zone. As reduction of power for the heating furnace was small, this heating furnace had been continuously operating for 5 days under seawater leakage condition. The leaked seawater changed into steam due to high temperature remained in the furnace and exhausted from the chimney of the furnace. Some part of high temperature steam will be absorbed into the insulation materials in the ceiling. In addition, the compensation of the skid pipes was repaired after stoppage and cooled down for 3 days and the ceiling insulating materials were continuously used as those stand.

3.2 Outer appearance of broken bolt

Figure 4.10 shows the outer appearance of broken bolts. These bolts were broken from the jointed portion to the steel plate and the surface of those was covered with brown rust. In addition, the rust color is printed into some parts of the inner insulating materials (black area of the silica board), where contacts to the steel plate. From the above fact, wet condition will be kept among steel plate, silica board and bolt.

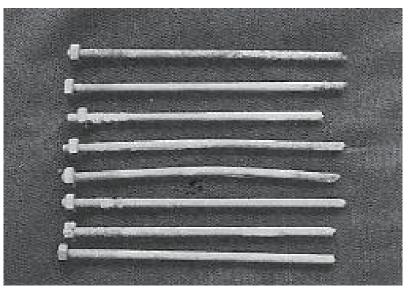

Fig.4.10 Outer appearance of broken bolts (ϕ6mm)

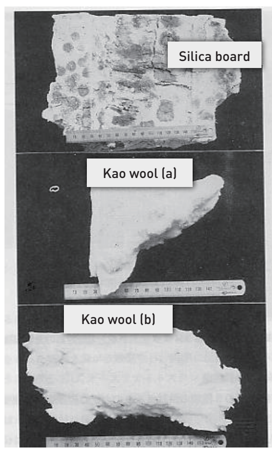

Fig.4.11 Outer appearance of thermal insulating materials near broken bolts

3.3 Results of investigation and discussion

(1) Production history of bolt

The bolt is made by the following process: cold drawing → solution treatment → thread rolling. The unused bolt that is made by the same lot as broken bolt was investigated about the microstructure of welded portion by resistance welding and shows the normal austenitic microstructure. **Table 4.2** lists the chemical composition and its analytical result shows within the specification of SUS304. Therefore, this bolt was not broken due to the production history of bolt.

Table 4.2 Chemical composition of SUS304 stud bolt (Mass,%)

	C	Si	Mn	P	S	Ni	Cr	Mo
Stud bolt	0.064	0.48	1.28	0.038	0.002	8.70	18.40	0.02
SUS304 Spec.	≦0.08	≦1.00	≦2.00	≦0.045	≦0.030	8.00~ 10.50	18.00~ 20.00	–

*Spec.; Specification

(2) Microscopic structure of bolt

Figurs 4.12 and 4.13 show microscopic structure of the vertical section of stud bolt, respectively. The plural micro-cracks are initiated from outer surface (bottom of pit) and propagate at a right angle to the axis of bolt along mainly grain boundaries like jigzag. The boundary carbide is precipitated in the overall length of the bolt. Therefore, it is considered that this bolt was heated in the high temperature of precipitation of boundary carbide between 400~800℃. However, as the above condition will be made after the fall of the insulating materials, the temperature of bolt in crack initiation, will be less than 400℃.

Figure 4.14 shows the optical microstructure of the vertical section of stud bolt and SCC cracks initiation. In addition, Fig. 4.15 shows the vertical section of broken stud bolt and its enlarged view of cracks. As can be seen from these figures, the cracks initiate from here and there in the case of SCC and propagate mainly along grain boundaries in association with trans-granular fracture. In addition, the cracks propagate into all of direction like a streak of lighting and show remarkable branching.

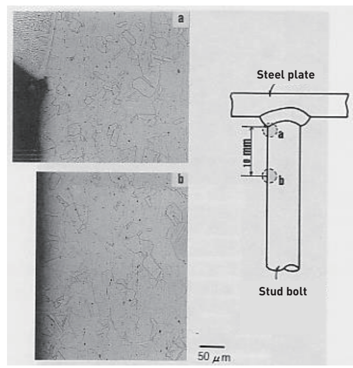

Fig.4.12 Optical microstructure of vertical section of an unused stud bolt

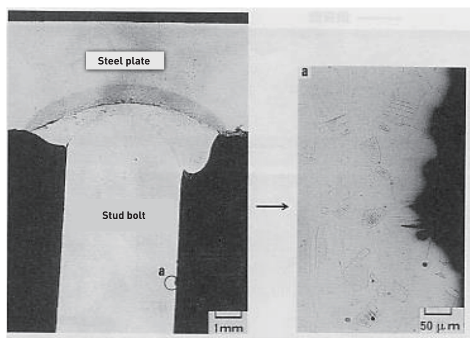

Fig.4.13 Vertical section of SUS304 stud bolt and its enlarged view of corrosion pits

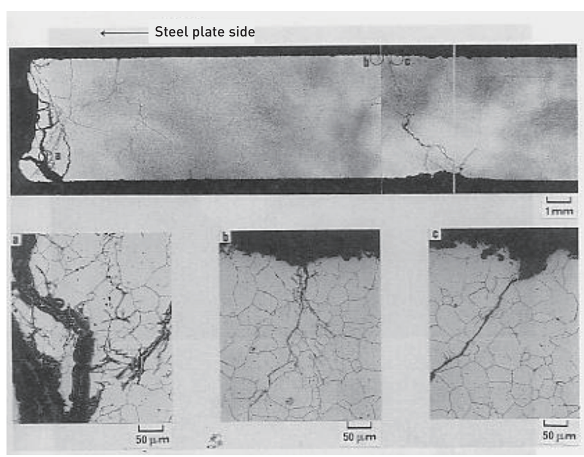

Fig.4.14 Vertical section of stud bolt and its microstructure of SCC

(3) Estimation of applied stress to the stud bolt by hardness distribution

Figure 4.16 shows hardness distribution of vertical section of stud bolts. The hardness of broken bolts (bolt A, B) and unused bolt are between Hv=170~230 and Hv=160~190, respectively. The former is higher than the latter by ΔHv=10~40 and this value will be caused due to work hardening during operation. At first, the axial tensile stress, which supports the insulating materials, is 0.69MPa, whose stress cannot affect work hardening to the stud bolt. There is high possibility about the following stress: vibration during operation of heating furnace → shake of the insulating materials and bolts laterally → bending stress at the jointed portion of bolt. In addition, the cold working ratio will be estimated to be 1~4% due to the increase of ΔHv=10~40 [4)6)] (ref. Fig.4.17). The hardness of bolt C (△) shows the same value as unused bolt and this phenomenon will be caused that the stud bolt becomes heated until high temperature of precipitation of intergranular carbide and applied by stress relief annealing (SR), then work hardening due to applied stress will disappear.

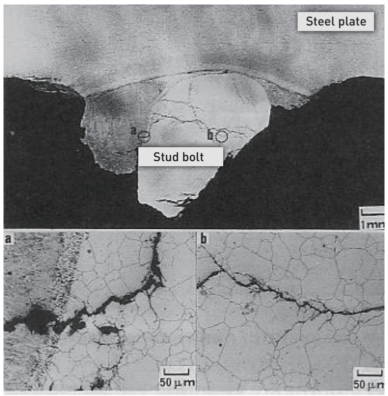

Fig.4.15 Vertical section of broken stud bolt and its enlarged view of cracks

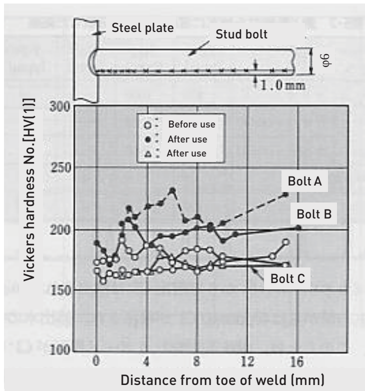

Fig.4.16 Hardness distribution of vertical section of stud bolts

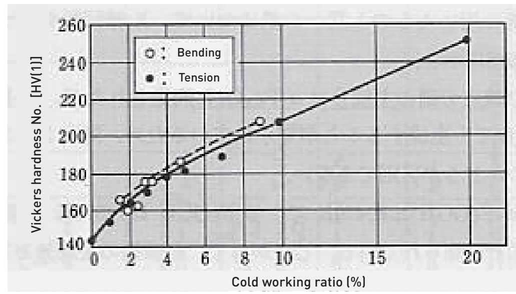

Fig.4.17 Relation between cold working ratio and Vickers hardness No. of SUS304

(4) Chemical analysis of corrosive compound

The rust of stud bolt and steel plate and the three kinds of insulating materials are analyzed by resolving in pure water (35℃, 200ml) with stirred and filtrated solution. **Table 4.3** lists the chemical composition of the above rust and insulating materials. As can be shown from this table, Cl^{-1} is detected from the steel plate by 150ppm and from the insulating materials, which contacted to the steel plate, by 400ppm. As Cl^{-1} in unused silica board is contained 35ppm, it condenses by 4~10times in the area between steel plate and silica board. On the other hand, the dissolved Cl^{-1} is not detected in the intermediate insulating material [Cao wool (a)] and the exterior one [Cao wool (b)]. In addition, Cl^{-1} is detected in the rust of broken bolt by 40ppm and pH of dissolved water shows just about neutral. This means the boundary between bolt and silica board is in the state of damp containing Cl^{-1} and crevice corrosion (pitting) and SCC will easily appear in the boundary (see **Table 4.4**).

Table 4.3 Chemical composition about rust and insulating materials dissolved in pure water

Materials		Cl^- (ppm)	SO_4^{2-} (ppm)	Na^+ (ppm)	T, Fe (ppm)	pH
Insulating materials	Silica board	400	1,000	_	_	_
	Kao wool (a)	0	1,000	_	_	_
	Kao wool (b)	0	2,800	_	_	_
Rust of stud bolt		40	0	0	0	6.5
Rust of steel plate		150	0	0	110	6.8

Table 4.4 Used condition of stud bolt

Strain (%)	Cl^-(ppm)	Temperature (℃)	pH
1 ~ 4	40 ~ 400	60 ~ 400	6.5 ~ 6.8

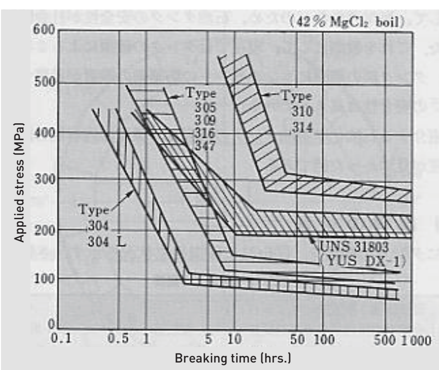

Fig.4.20 Relative SCC resistance of stainless steels

Figures 4.18 and 4.19 show X-ray diffraction pattern of the rust on the surface of stud bolt, the steel plate and chemical analysis, respectively. In addition, Fig. 4.20 shows relative SCC resistance of stainless steels and this relative resistance shows higher value in the upward and right hand side direction.

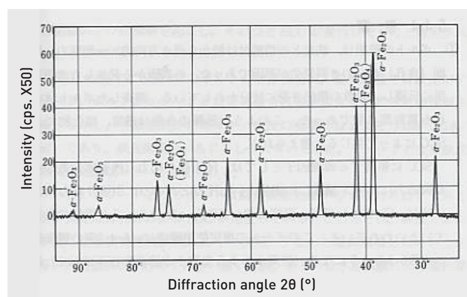

Fig.4.18 X-ray diffraction pattern of rust on stud bolt surface and chemical analysis

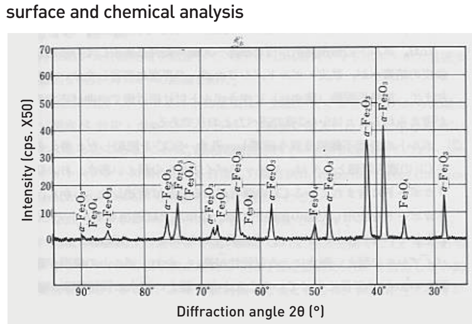

Fig.4.19 X-ray diffraction pattern of rust on steel plate surface and chemical analysis

3.4 The summary and countermeasures

The following summary and countermeasures are listed according to the investigation of the mass failures of stud bolts made of SUS304, which happened about the heating furnace for steel blooms. The failures of SUS304 stud bolts will be caused by SCC due to leakage of seawater from skid pipe of the heating furnace and its intrusion into steel plate, bolts and silica board. This phenomenon will be recently considered to be the same matter as the external stress corrosion cracking, ESCC) of austenitic stainless steels into the insulating materials. In addition, invasion of Cl^{-1} from silica board into the failure portion will be considered as one of the cause for the above failures.

The countermeasure of the above failures is to prevent the invasion of Cl^{-1} into the above environment. That is, the careful maintenance and management will be requested to prevent the leakage of seawater from skid pipe and to use the insulating materials free from Cl^{-1} and to use anti-SCC steels. The SCC resistance of stainless steels from intergranular fracture shows the following order; SUS304 < SUS316 < SUS310S < SUS430, 15/18Cr-12/15Ni-3/5Si austenitic stainless steel. The life of heating furnace is about 10 years and SUS310S will be adequate in this case by considering into its weldability (see Fig. 4.20).

In complementary to the above, the former cases are due to stress corrosion crack. In the case of general stress corrosion crack, the cracks are initiated from here and there and the fracture surface shows jagged edge without macroscopic plastic deformation. ***The SCC cracks propagate not only inter-granularly but also trans-granularly with remarkable branching, which is different from the other fracture patterns. Therefore, not only the observation of fracture surface itself but also the vertical section will be important from the view point of correct judgement for the failures. That is, most of the researchers will observe the only fracture surface. On the other hand, they had better investigate not only fracture surface but also the vertical section to the fracture surface and decide the cause of failure by comparing the above fracture patterns.***

4. Conclusion

Though the screw fastened member between bolt and nut is one of the most representative connected part of machines and equipment, it will be treated to be a consumable part for exchanging the new one when it is failed. This report has introduced the representative two examples about environmental failure of bolts (stress corrosion crack, SCC). Summarizing the results of the investigation described above, the following items will be concluded.

(1) Failure of fastening bolt for the level gauge of an Ar-gas holder; the high tension bolt was tightened by large tightening axial force and corroded with corrosion pits , where is initiated to be stress corrosion crack. To prevent this cracking, it will be effective to decrease the strength of the high tension bolt by changing the heat-treating condition from H900 to H1075 and decrease the bolt-tightening torque from 2 kgf-m to 1kgf-m.

(2) Failure of stud bolt for the heating furnace; the failures of SUS304 stud bolts will be caused by SCC due to leakage of seawater from skid pipe of the heating furnace and its intrusion into steel plate, bolts and silica board. The countermeasure of the above failures is to prevent the invasion of Cl^{-1} into the above environment. That is, the careful maintenance and management will be requested to prevent the leakage of seawater from skid pipe and to use the insulating materials free from Cl^{-1} and to use anti-SCC steels. In addition, SUS310S will be adequate in this case by considering into its weldability.

References:

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