Failures of Screws and Their Preventive Methods

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—Environmental failure of bolts, (the first half), 3rd report—

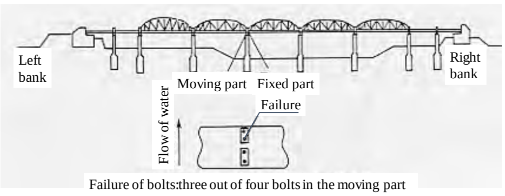


Fig.3.1 Condition of failure (see Fig.3.2)

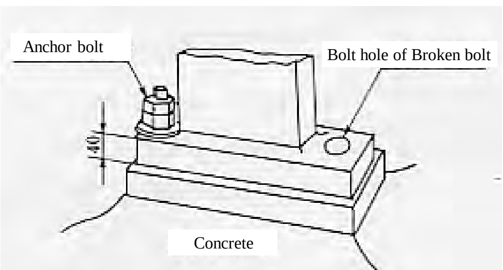


Fig.3.2 Anchor bolt set in place

1. Introduction

In the previous report, various kinds of the fatigue failure of bolts have been described. In this report, examples of environmental failure are referred. 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 a corrosive environment. This report introduces examples of environmental failure of bolts to which repeated stress is apparently not applied or very small repeated stress is applied.

2. Failure of anchor bolts for a water-tube bridge

2.1 Outline of failure

During his round of inspection, an inspector found broken bolts scattered on the dry ground on the river. The bolts were assumed to be the ones used in a water-tube bridge. On closer inspection, it was found that they were anchor bolts used in the moving part of a bridge pier. The condition of failure is shown in Fig.3.1 Three out of four bolts were broken and their nuts were scattered on the dry ground (ref. Fig.3.2). The bolts had been in service for 14 years and 9 months before their failure was detected.

2.2 Items investigated

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

(2) Inspection of outer appearance

(3) Mechanical properties (hardness distribution)

(4) Observation of fracture surface by SEM (Scanning Electron Microscope).

The sampling procedure is shown in Fig.3.3.

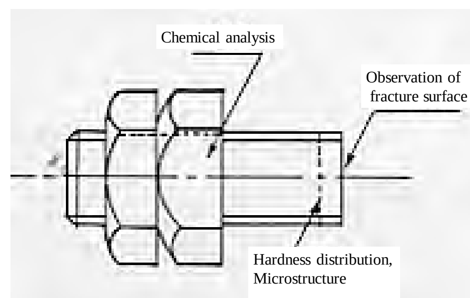


Fig.3.3 Sampling procedure

2.3 Results of investigation and discussion

(1) An appearance of the broken bolt

Figure 3.4 shows the appearance of the broken bolt. The failure initiated at a point about 47mm from the end section of the nut. This distance is exactly equal to the sum (46mm) of the thickness of the fastened part (40mm) and the thickness of the washer (6mm). The broken bolt was fairly corroded and the fracture surface was not clear because of corrosive rust. However, careful observation revealed a faint pattern extending in the a—b direction which looks like a crack propagation pattern [ref. Fig.3.4(e)]. This direction is considered as the standard direction in Fig.3.4. The diameter in the standard direction is shorter by about 3mm than that in a direction at right angles to the standard direction.

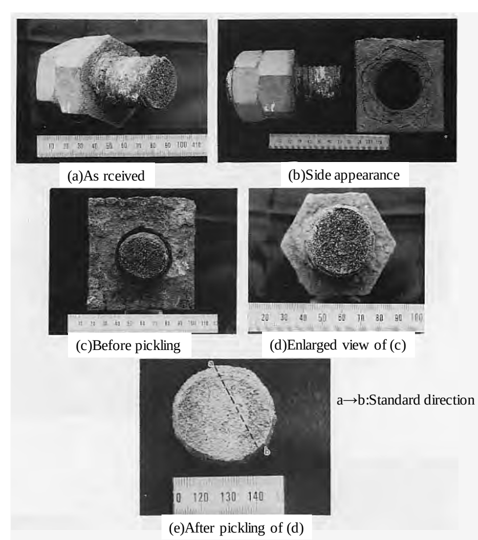


Fig.3.4 Outer appearance of broken bolt

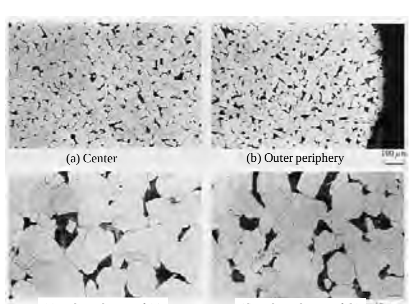


Fig.3.5 Microstructure of transverse section

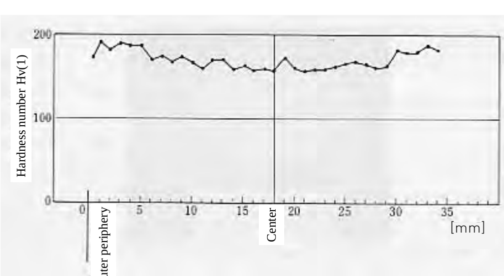


Fig.3.6 Hardness distribution

Table 3.1 Chemical composition (Mass %)

C	Si	Mn	P	S	Ni	Cr	Cu	Mo	B	Al
0.13	0.29	0.36	0.029	0.034	0.11	0.10	0.34	0.01	0.0001	0.004

(2) Steel grade of broken bolt

The chemical composition and optical micrograph of the broken bolt are shown in Table 3.1 and Fig.3.5, respectively. The hardness distribution in the bolt is shown in Fig.3.6. On the basis of these

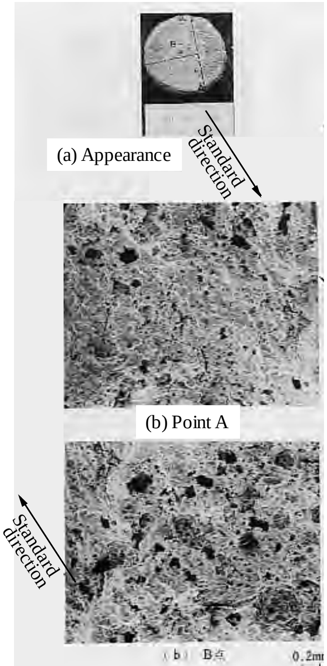


Fig.3.7 Result of observation of fracture surface by SEM

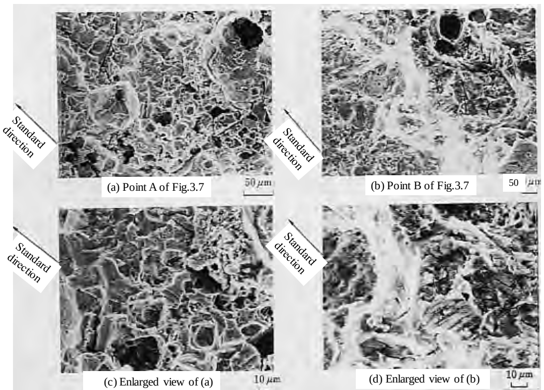


Fig.3.8 Results of observation of fracture surface by SEM

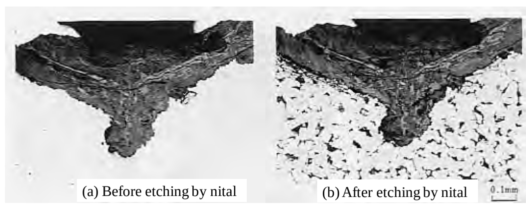


Fig.3.9 An example of corrosion pit at the root of thread

data, the steel grade of the steel is considered to be equivalent to JIS, SS400 (a representative mild steel). The structure is the typical ferrite-pearlite structure observed in low-carbon steels.

(3) Observation of the fracture surface

The results of observation of the fracture surface are shown in Figs.3.7 and 3.8. As the bolt was exposed to a corrosive environment for a long period of time, an infinite number of corrosion pits is observed. It seems that changes were caused in the fracture surface due to the formation of a rust layer. Although not clearly seen, there is a striation-like pattern [see Fig.3.8(d)], and fissures are frequently observed in the fatigue fracture surface [see Fig.3.8(a)].

(4) Example of corrosion pits at the thread root

An example of the corrosion pits at the thread root is shown in Fig.3.9. Figure 3.9(a) is the structure before etching and (b) shows after etching with nital. The depth of corrosion pits at the thread root is about 0.2mm. In addition, the width of the pits is about also 0.2mm.

2.4 Summary

The bolt is made of a steel equivalent to SS400. No trace of macroscopic plastic deformation is observed on the fracture surface. The diameter in the direction which is supposed to be the direction of crack propagation is shorter by about 3 mm than the diameter in a direction at right angles to the above direction. The position of failure is the bottom end of the fastened part but not the end section of the nut where the maximum stress usually develops. A striation-like pattern and fissures are seen on the fracture surface, although not clearly. On the basis of these results, the cause of failure of the bolt is estimated to be fatigue failure caused by the cyclic shear stress induced with the repeated application of the shear force which had been produced by the expansion and contraction of the bridge pier during about 15 years in service accompanying with tensile stress . Moreover, the corrosive atmosphere is also responsible. Accordingly, the diameter on the side where the shear force was applied is smaller by about 3 mm.

As a countermeasure, the anchor bolt hole should be enlarged in consideration of the thermal expansion of the bridge pier, or the anchor bolt should be set nearly at the center of the bolt hole so that it is not affected by the thermal expansion of the bridge pier.

3. Failure of fastening bolt for the small bell rod flange of a blast -furnace

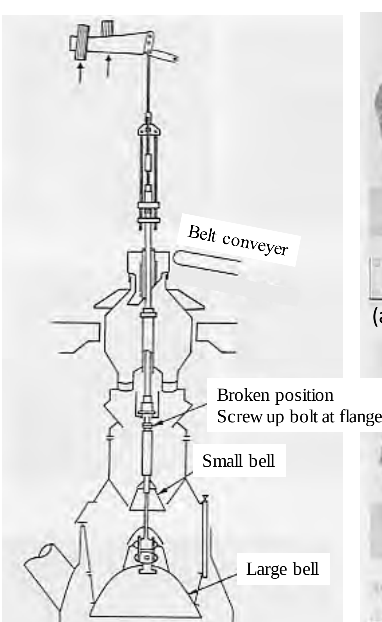


Fig.3.10 Schematic drawing of blast-furnace top position of failure in the bolt

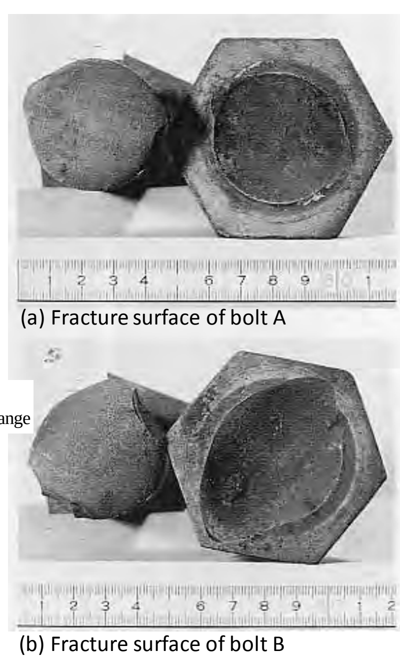


Fig.3.11 Outer appearance of fracture surface of bolt

3.1 Outline of failure

All 20 fastening bolts for the small bell rod flange installed at the top of a blast-furnace broke after 6 months of service. Bolt details: steel grade, SCM435 (QT steel), M42×190 mm in length, thread length, 87 mm, stress applied to the bolt, repeated stress amplitude $\sigma a=2.9\ kgf/mm^2$, mean stress $\sigma m=10.4\ kgf/mm^2$. In addition, the bending stress was also applied (see Fig.3.10).

3.2 Items investigated

Nearly the same as those described in Section 2.2.

3.3 Results of investigation and discussion

(1) Appearance of the broken bolt

Out of 20 bolts, 18 bolts were broken under the head (R=0.7 mm) and two bolts at the end section of the nut (although the number of the broken bolts that could be collected was 15). The surface of the broken bolts was fairly corroded. In some bolts, axial bending and cracks at the thread root were detected (see Fig.3.11).

(2) Chemical composition and hardness distribution

Table 3.2 shows the chemical composition of the bolt. The composition satisfies the JIS standard. The hardness distribution is shown in Fig.3.11. As there is a difference of 25% in hardness in the transverse section of the bolt, it is considered that the tempering of the bolt was insufficient, causing embrittlement of the surface.

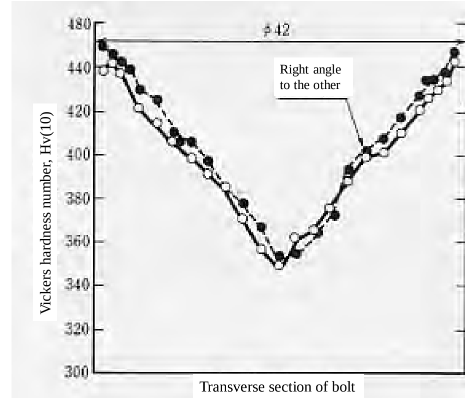


Fig.3.12 Hardness distribution in transverse section of bolt

Table 3.2 Chemical composition (Mass%)

Remarks	C	Si	Mn	P	S	Cu	Cr	Mo	Al
Bolt A	0.36	0.25	0.79	0.027	0.013	0.03	1.00	0.18	0.054
Specification	0.32 ~0.39	0.15 ~0.35	0.55 ~0.90	≥0.030	≤0.030	≤0.030	0.85 ~1.25	0.15 ~0.35	—

(3) Observation of the fracture surface

The results of observation are shown in Fig.3.11 and Figs 3.13 and3.14. At the failure initiation point in the fracture surface, transgranular failure and intergranular failure coexist, with the former type predominating. The transgranular fracture surface resembles the fatigue surface of high strength steel but no striation is observed in it.

At a point 5-10 mm from the failure initiation point, the transgranular failure and intergranular failure coexist but the proportion of intergranular failure is higher (see Figs 3.13 and 3.14). Dimple and river patterns coexist in the final fracture surface.

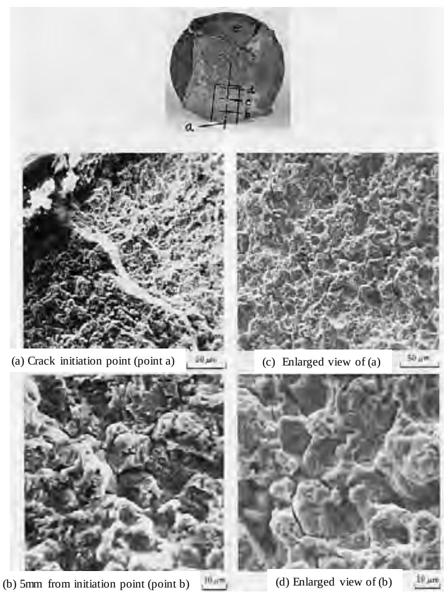


Fig.3.13 Results of observation by SEM of fracture surface of bolt A

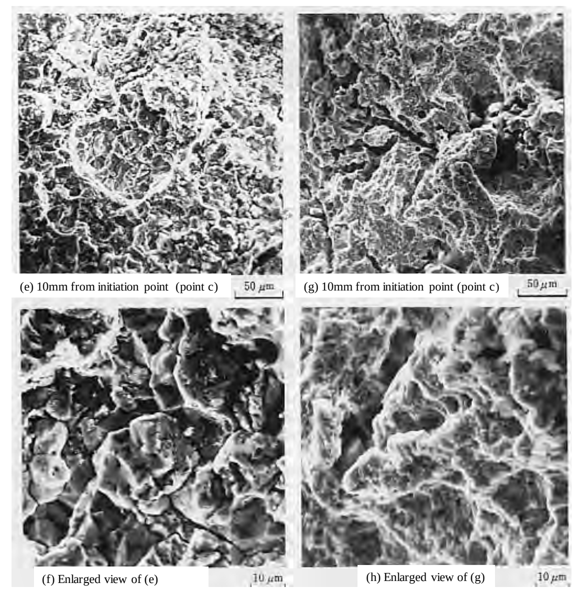


Fig.3.14 Results of observation by SEM of fracture surface of bolt A

3.4 Summary

On the basis of the results described above, it is considered that fatigue cracks were caused by the stress concentration under the head of the bolt and their propagation was accelerated by the corrosive environment, finally resulting in failure.

To prevent failure, the following methods are suggested:

(1) An increase in radius under the head (R=0.7→5.0mm for M42 thread).

(2) Equalization of axial tension in the bolt to be an appropriate value by controlling the tightening torque.

(3) A decrease in surface hardness by tempering at 550—650□, and rust-preventive treatment.

4. Failure cases by delayed fracture of bolt

4.1 Mechanism of delayed fracture

As is generally known, delayed fracture initiates after service or after certain amount of time. That is, delayed time exists before crack initiation. Those are ① the time until corrosion, ②the time when hydrogen intrudes into steel and ③the time when hydrogen concentrates into crack initiation point.

Figure 3.15 shows initiation condition of delayed fracture. As is shown in this figure, delayed fracture initiates when material, stress and environment satisfy a certain condition. As several models have been already presented, most general one is illustrated in Fig. 3.16.

In natural corrosion: Anode reaction, $Fe \rightarrow Fe^{++} + 2e$ ***......(1)***

Cathode reaction,

Acid corrosion, $2H^{+} + 2e \rightarrow H_2\uparrow$ ***......(2)***

Neutral or alkali corrosion,

$2H_2O + 2e \rightarrow H_2\uparrow + 2OH^{-}$ ***......(3)***

In the above equations, the reaction that hydrogen ion changes into hydrogen gas, occurs in the grain boundary. It is considered that the facture appears when hydrogen gas pressure exceeds the critical one.

Delayed fracture initiates when stress, material and environment satisfy specific condition.

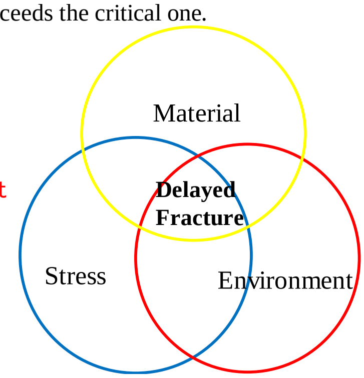


Fig. 3.15 Initiation condition of delayed fracture

[Corrosion]

Anode reaction : $Fe \rightarrow Fe^{++} + 2e$ ········· (1)

Cathode reaction: :

Acid corrosion $2H^{+} + 2e \rightarrow H_2\uparrow$ ········· (2)

Neutral or alkali corrosion

$2H_2O + 2e \rightarrow H_2\uparrow + 2OH^{-}$ ········· (3)

When corrosion pit initiates, unstable corrosive constituent hydrolizes itself and increases the hydrogen density and accelerates reaction (2) in corrosion pits even in neutral environment.

$FeCl_3 + H_2O \rightarrow FeOH^{2+} + 3Cl^{-} + H^{+}$ ········· (4)

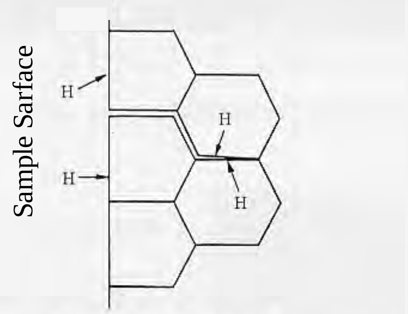


Fig.3.16 A model of delayed fracture (5)

4.2 Examples of delayed fracture of high tension bolts

A large number of bolts are used in the connected portion of steel construction under building with backing plates from both sides. These are typical example of high tension bolt. The axial load in steel frame work stands against the frictional load between backing plate and fastened member with the fastening stress by high tension bolt. For example, as far as the symbol of F10T at the head, F means "for Friction Grip Joint", 10 is from tensile strength of 100 kgf/mm^2 and T is from "Tensile strength", this means the grade of mechanical properties. In addition, high tension bolt shows the following advantages; ①to get high reliable connected portion, ②to be able to operate easily even in height works with simple fastening tools, ③no residual strain in the fastened portion, etc. The weight percentage of high tension bolts occupies 2.5〜3.0% of the whole steel constructions due to the above many advantages.

Figure 3.17 shows a fracture surface by delayed fracture of bolt. Though the record of this bolt in service is not clear at present, this is a representative delayed fracture of bolt. As the fringe part is external thread, the fracture is initiated from the end section of nut. The point A in Fig.3.17 is crack initiation one, propagate into the point B and to be a final fracture. The crack initiation point in this case is about 0.5mm inside from the bottom of thread. Figure 3.18 shows the enlarged view of point A in Fig.3.17. As shown in this figure, the hollows in the left and right-hand sides of the crack initiation point A is corrosion pits and these are generated in corrosive atmosphere. The enlarged view of (a) in Fig.3.18 is shown in (b). There intergranular fracture surface is observed in the crack initiation point. In addition, the transient area to final fracture is point B as shown in Fig.3.19. Though almost all area is occupied with transgranular fracture, the intergranular fracture also remains a little in this surface. The intergranular fracture resembles to half-melted candy, this is also called as "candy block". The delayed fracture as predicted the above can be understood by the model shown in Fig.3.16.

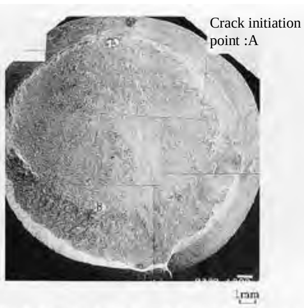


Fig.3.17 Delayed fracture of high tension bolt (σB=1,100MPa)

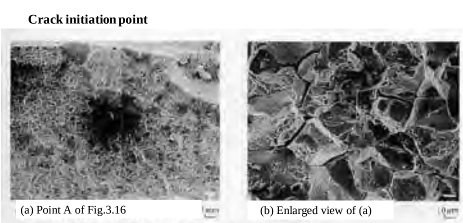


Fig.3.18 Delayed fracture of high tension bolt (enlarged view of point A in Fig.3.16)

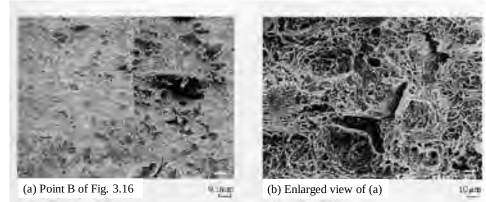
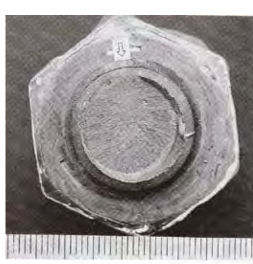


Fig.3.19 Delayed fracture of high tension bolt (enlarged view of B point in Fig.3.16)

Figure 3.20 shows another example by delayed fracture of high tension bolt. This bolt is M22 in nominal diameter and contains boron (B) with tensile strength of 1,250MPa. In addition, the bolt has been used in industrial area along seashore for less than 19 years. The microscopic fracture surfaces by SEM are shown in Figs.3.21 and 3.22 respectively. The intergranular fracture surfaces are observed in these figures. The corrosive pits in intergranular fracture surface will be made by exposing in the corrosive atmosphere at industrial area after broken by delayed fracture. In the case of delayed fracture of bolt, the crack is mostly generated from incomplete thread and also generated from underhead fillet. The fracture from underhead fillet can be explained by the drop of water gathered in this area in the case of the bolt head settled downward or by the stress concentration due to the contact of washer to underhead fillet.



Arrow mark: crack initiation point

Fig.3.20 Outer appearance of delayed fracture of high tension bolt

Size:M22、B includes、Quenced and tempered、
Tensile strengthσ_B＝1,250MPa
Environment：seaside、industrial area,
Service time: within 19 years
(the fractured bolt was found in 19th year)

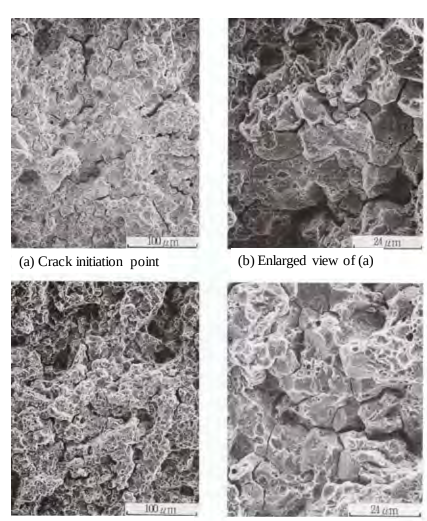


Fig.3.21 Observation results by SEM delayed fracture(6)

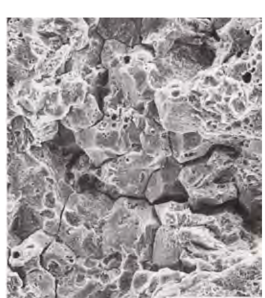


Fig.3.22 Results of observation by SEM of delayed fracture(6) (enlarged view of Fig.3.20)

In any case, it is considered that delayed fracture is related to hydrogen as shown in crack initiation condition of delayed fracture and also called to be "hydrogen embrittlement, i.e. HE". The Society of Japanese Steel Construction (JSSC) has prohibited or recommended not to use the high tension bolts higher than F11T. In addition, the makers of high tension bolt had developed about the new type of high tension bolt for anti-delayed fracture from the viewpoint of stress concentration at incomplete thread and improvement of chemical composition and developed F12T and F14T (included to equivalent bolts) under the certain limitation.

5. Conclusion

(1) On the basis of these results, the cause of failure of the bolt is estimated to be fatigue failure caused by repeated application of the shear force produced by the expansion and contraction of the bridge pier during about 15 years in service. Moreover, the corrosive atmosphere is also responsible.

(2) As a countermeasure, the anchor bolt hole is enlarged in consideration of the thermal expansion of the bridge pier, or the anchor bolt is set nearly at the center of the bolt hole so that it is not affected by the thermal expansion of the bridge pier.

(3) On the basis of the results described above, it is considered that fatigue cracks were caused by the stress concentration under the head of the bolt and their propagation was accelerated by the corrosive environment, finally resulting in failure.

(4) To prevent failure, the following methods are suggested:

① An increase in radius under the head (R=0.7→5.0mm for M42 thread),

② Equalization of axial tension of the bolt to an appropriate value by controlling the tightening torque

③ A decrease in surface hardness by tempering at 550−650℃, and rust-preventive treatment.

(5) As far as delayed fracture of bolt, the crack initiation point is inside from the bottom of thread with accompanying with corrosion pits. The intergranular fracture also observed at the crack initiation point. In addition, the intergranular fracture pattern resembles to half-melted candy, this is called also as “candy block”.

In any case, it is considered that delayed fracture is related to hydrogen and this fracture is called “hydrogen embrittlement, HE” in other words.

References

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