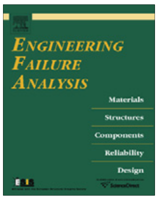
Engineering Failure Analysis 18 (2011) 1735–1741

Contents lists available at ScienceDirect

Engineering Failure Analysis

journal homepage: www.elsevier.com/locate/engfailanal



# Failure analysis of a pressure vessel bolt in a nuclear fuel fretting wear simulator

Young-Ho Lee *, Hyung-Kyu Kim

*Korea Atomic Energy Research Institute, 150 Dukjin-dong Yuseong-gu, Daejeon 305-353, Republic of Korea*

ARTICLE INFO

*Article history:*
Received 30 July 2010
Accepted 29 March 2011
Available online 2 April 2011

*Keywords:*
Failure analysis
Fretting wear simulator
Pressure vessel bolt
Fracture surface

ABSTRACT

This paper presents a failure analysis on a pressure vessel bolt of a fretting wear simulator. After 500 h tests, in an upper pressure vessel of a fretting wear simulator, one bolt among eight was fractured near the bolt neck regions. The fracture surface was examined by using a scanning electron microscope (SEM) to determine the failure initiation and failure mode. The result indicates that the fracture surface shows intergranular fracture features. Based on the mechanical property data of a bolt material, it is concluded that the exerted stress on the bolt applied by an internal pressure of the pressure vessel has a negligible effect on the major failure causes. In order to verify the mechanical properties of the fractured bolt, tensile test has been performed and its result was compared with material specification. As a result, it is thought that both excess heat treatment during the surface hardening procedure and loose parts in the thread hole have significant effects on the pressure vessel bolt failure. In this paper, the reasons for this failure were discussed by using metallographic studies of the failure surface, mechanical tests with the failed bolt and the stress distribution of the contact regions with considering loose parts by using FE analysis.

## 1. Introduction

A vertical type of a fretting wear simulator for high temperature and pressure water condition was developed for evaluating the fretting wear behavior of nuclear components [1]. This simulator was applicable to the evaluation of fretting wear damages due to a flow-induced vibration (FIV), which have been experienced in relatively slender structures such as nuclear fuel rods, steam generator tubes and control rods [2]. After 500 h test, however, one bolt among eight was fractured near the bolt neck regions in an upper pressure vessel as shown in Fig. 1. Considering the system performance at high temperature and pressure conditions, the reliability of the pressure bolt should be sufficiently satisfied during services. In this study, the failed bolt was inspected to identify the reasons for the rapid rupture. The possible failure causes were assessed and discussed by using SEM observation of the fracture surface, measurement of the micro-vickers hardness, tensile test with the failed bolt and stress analysis of the pressure vessel bolt with considering loose parts in the thread hole.

## 2. Investigation methods

The failed pressure vessel bolt used in this simulator is a conventional high-carbon martensitic stainless steel (SUS 440C). This material is widely used as tools or blades in relatively corrosive atmospheres [3]. After machining to fit the system performance, these bolts were heat-treated in order to increase surface hardness for preventing the thread wear of the bolt

---

* Corresponding author. Tel.: +82 42 868 8761; fax: +82 42 863 0565.
*E-mail address:* leeyh@kaeri.re.kr (Y.-H. Lee).

1350-6307/$ - see front matter © 2011 Elsevier Ltd. All rights reserved.
doi:10.1016/j.engfailanal.2011.03.024

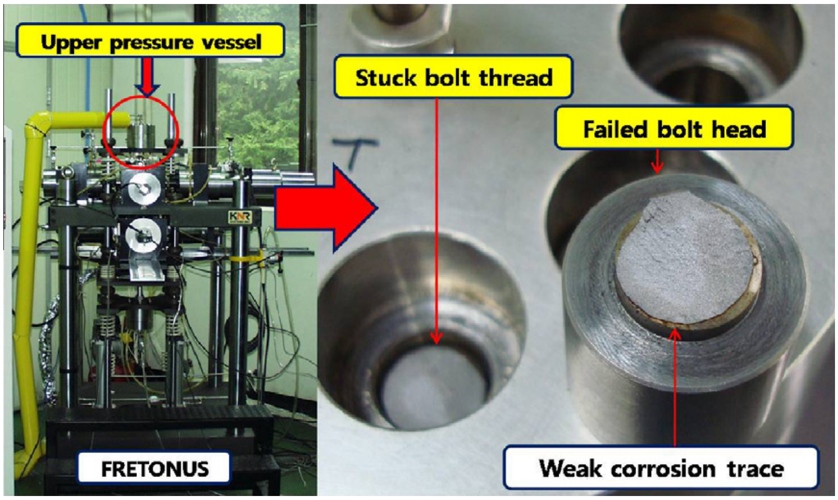


**Fig. 1.** The schematic views of a fretting wear simulator (FRETONUS) and photograph showing the failed bolt in a upper pressure vessel.

during the autoclave cover being repeatedly bolted. The chemical composition and mechanical properties are listed in Tables 1 and 2 [4].

The exerted force on each bolt of the autoclave ($f_b$) is simply calculated as follows;

$$f_b = 1/8 \cdot P_i \cdot (\pi \cdot D_A^2/4) = 3.6\ \text{kN} \tag{1}$$

where, $P_i$ is internal pressure (15 MPa) and $D_A$ is diameter of autoclave (50 mm). The exerted stress on each bolt ($P_b$) is

$$P_b = f_b/(\pi \cdot D_b^2/4) = 24\ \text{MPa} \tag{2}$$

where, $D_b$ is the diameter of the pressure vessel bolt (14 mm). This value is negligible to compare with a material specification of the bolt as listed in Table 2. Therefore, the pressure bolt seemed to be failed by either metallurgical defects or the excess stress caused by bolting the pressure vessel cover. In this study, two failure possibilities were examined. One is material degradation effect caused by the excess heat-treatment. The other is loose parts effect in the thread hole of the pressure vessel, which will be mentioned later.

## 3. Examination of the failure causes

### 3.1. Failure surface analysis

Fig. 2 shows the SEM result on the fracture surface of the pressure vessel bolt. It is apparent that the fracture surface shows the intergranular fracture feature. There is no fatigue failure mode such as regular striation traces on the fractured surface. In addition, corrosion damages as shown in Fig. 1 were distributed around the thread region of the bolt neck while the fracture surface was not oxidized regardless of the high temperature condition. However, it is difficult to detect the circumferential cracks on the fracture surface. These results indicate that the pressure vessel bolt was expected to rapid rupture after the fretting wear test has been finished because there was no leakage in an upper pressure vessel of the fretting wear simulator during the test. The important result of the failure surface analysis is that the pressure vessel bolt has been fully heat-treated during the surface hardening procedure. It can cause a brittle fracture mode if the stress condition was rapidly changed by thermal stress during the system cooling. So, it is necessary to examine the variation of the mechanical properties of the failed bolt.

**Table 1**
Chemical compositions of a conventional high-carbon martensitic stainless steel (SUS 440C) [4].

| C | Mn | Si | P | S | Cr | Mo | Fe |
|---|---|---|---|---|---|---|---|
| 1.0 | 1.0 | 1.0 | 0.04 | 0.03 | 17 | 0.75 | Bal. |

**Table 2**
Mechanical properties of SUS 440C at room temperature [4].

| Yield strength | Tensile strength | Elongation | Elastic modulus | Density | Poisson's ratio |
|---|---|---|---|---|---|
| 1280 MPa | 1750 MPa | 4% | 200 GPa | 7.8 g/cm$^3$ | 0.3 |

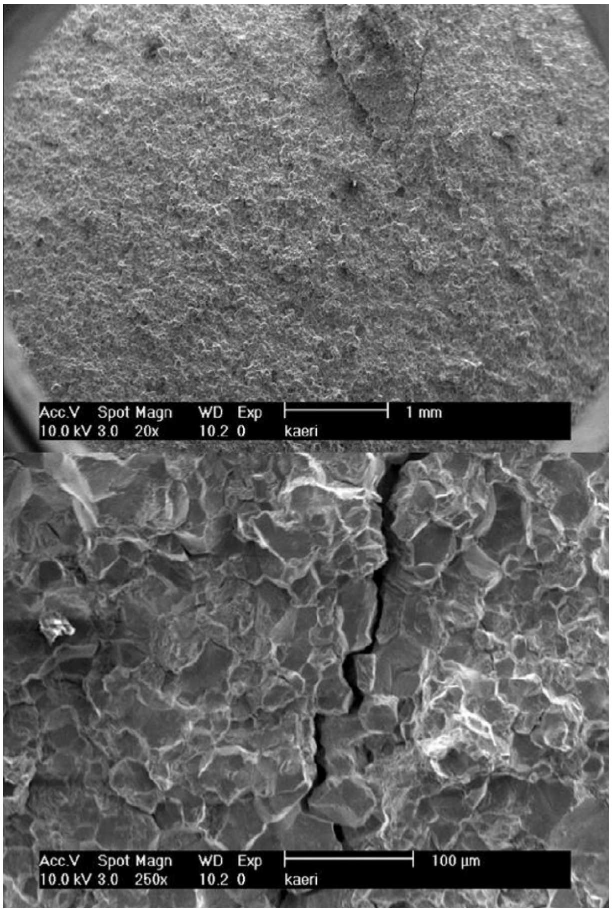


**Fig. 2.** SEM micrograph of the fractured surface of the pressure vessel bolt.

### *3.2. Mechanical tests by using the failed bolt*

Fig. 3 illustrates the preparation of the tensile specimen by using the failed bolt. First, the thread region of the failed bolt was carefully removed from the pressure vessel. Next, the removed bolt thread region was machined and parted to four sections. Finally, four tensile specimens were fabricated with 18 mm of the gauge length and 3 mm of diameter. Before the tensile test, it is necessary to verify whether the excess heat treatment was carried out during the surface hardening process. So, a micro-vickers hardness of the fractured pressure vessel bolt was measured by using a conventional hardness tester (SHIMADZU HMV-2T) with 10 s of loading time and its result was shown in Fig. 4. It is apparent that the micro-vickers hardness value did not show a noticeable change between the bolt surface and internal matrix. So, it is expected that the applied heat treatment condition was not suitable for the bolt surface hardening.

The tensile test has been performed by using a universal tensile tester (INSTRON 8801 model) with a loading rate of 0.125 mm/s and the typical result was shown in Fig. 5. As a result, the yield stress at 0.2% offset and ultimate tensile strength (UTS) show higher values when compared with the material specification of a conventional SUS 440C as listed in Table 2. This result confirms that the failed bolt was fully hardened by the faulted surface hardening condition. Generally, martensite stainless steel with a relatively higher carbon is likely to retain a large amount of untransformed austenite phase [3]. So, the operating temperature at upper autoclave region was expected about 150 °C, which had a negligible effect on the stress relieving of the pressure vessel bolt. Consequently, the fully heat-treated pressure vessel bolt shows some loss in ductility and failed due to the rapid change of the stress condition after service.

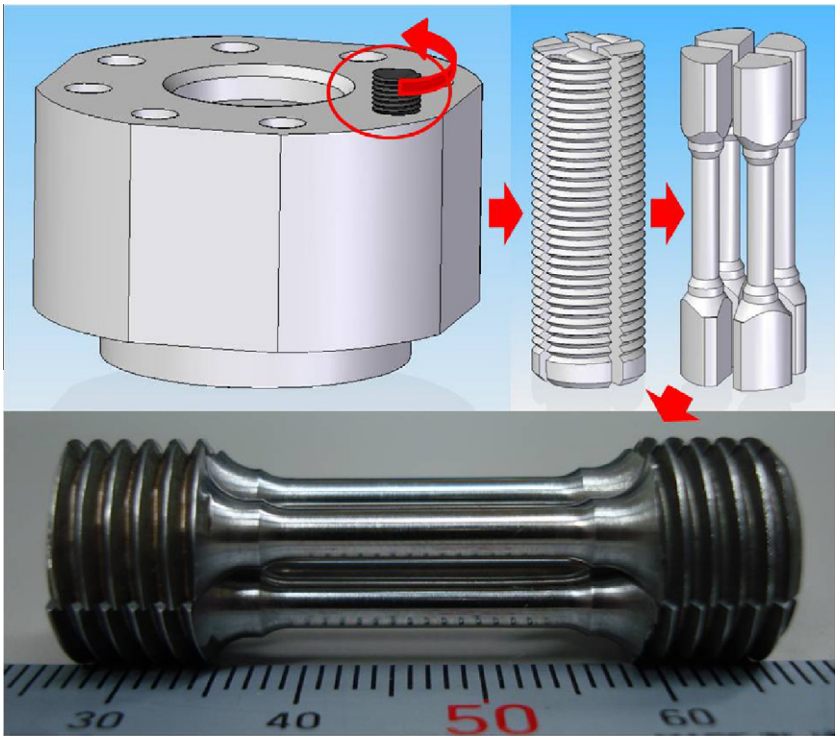


**Fig. 3.** Preparation procedure of the tensile specimen by using the failed pressure vessel bolt.

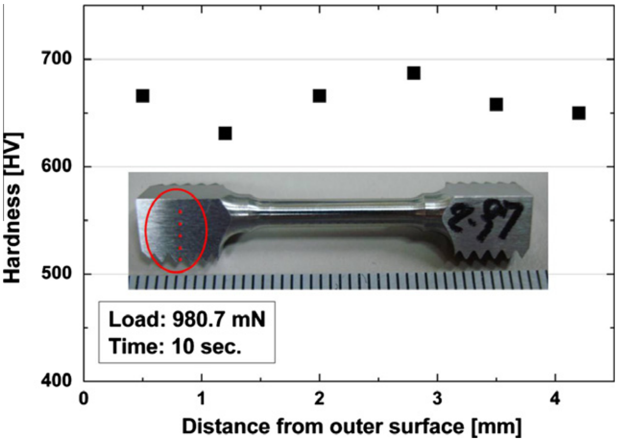


**Fig. 4.** Measurement result of the micro-vickers hardness.

### *3.3. SEM observation and loose parts*

Fig. 6 shows the morphology of fracture surface of the tensile specimen by using SEM. The fracture surface of the tensile specimen was mixed with the intergranular fracture and the dimple rupture. Also, it is difficult to detect the cleavage or quasi-cleavage fracture, which is the evidence of the brittle fracture. When compared with the failed bolt surface, the micro-crack network was well-developed and propagated to the intergranular mode in the fracture surface of the tensile specimen while relatively large cracks were propagated in the failed bolt as shown in Fig. 2. This morphology difference was expected to result from the loading rate. Consequently, the unexpectedly excessive stress was generated and exerted on the pressure vessel bolt because it is difficult to explain only the small amount of tensile force due to the internal pressure and the ductility loss of the failed bolt.

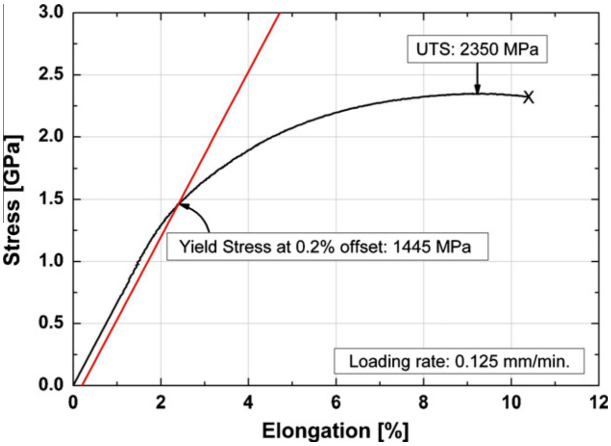


**Fig. 5.** Typical result of the tensile tests by using the failed bolt.

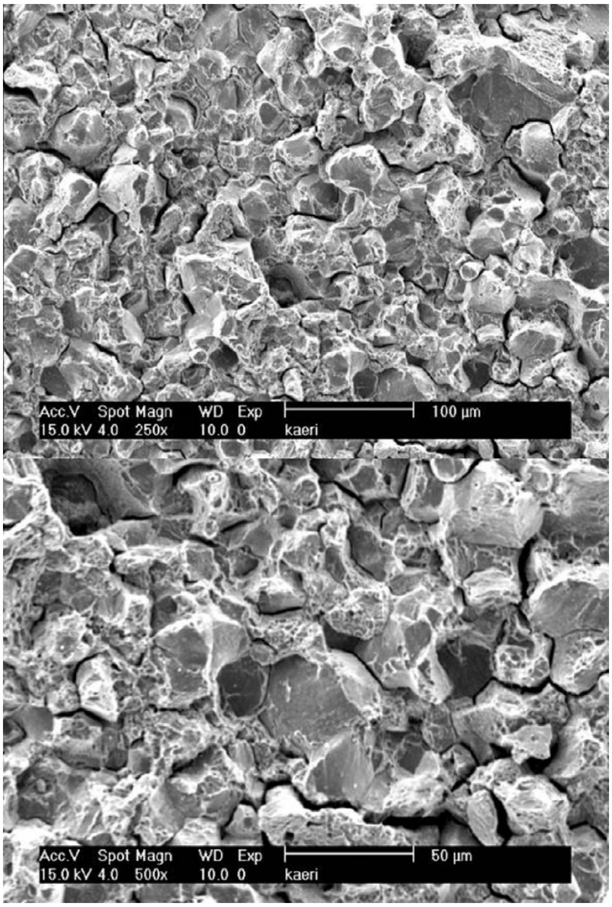


**Fig. 6.** SEM micrograph of the tensile specimen by using the failed bolt.

From a careful inspection of the autoclave thread hole, however, some loose parts was found and these consist with heavily oxidized taper chip and unknown parts as shown in Fig. 7. It is thought that, when the pressure vessel cover was bolted with the torque of 60 N m on each bolt, the excess stress could be generated if the end region of the bolt thread were contact with the loose parts or these were trapped in the gap between the bolt and thread hole. In order to verify this possibility, it is necessary to examine the stress distribution exerted on the bolt neck region with considering the remained loose parts in the thread hole of the autoclave.

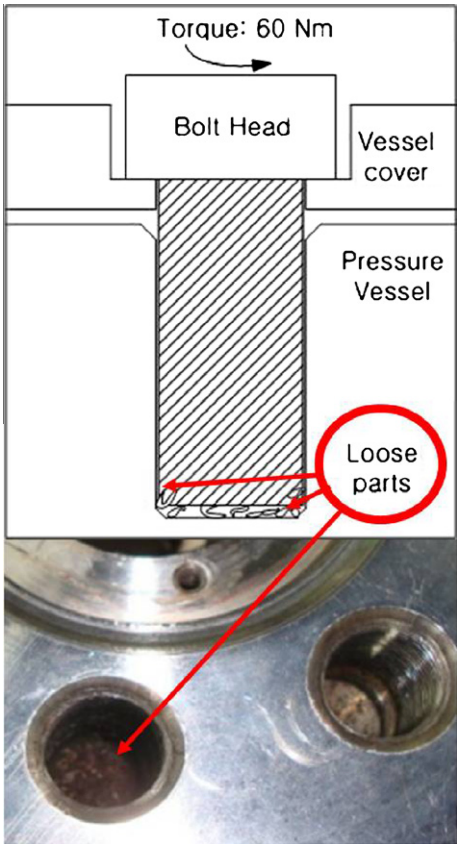


**Fig. 7.** The possibility of excess stress due to the loose parts in the thread hole.

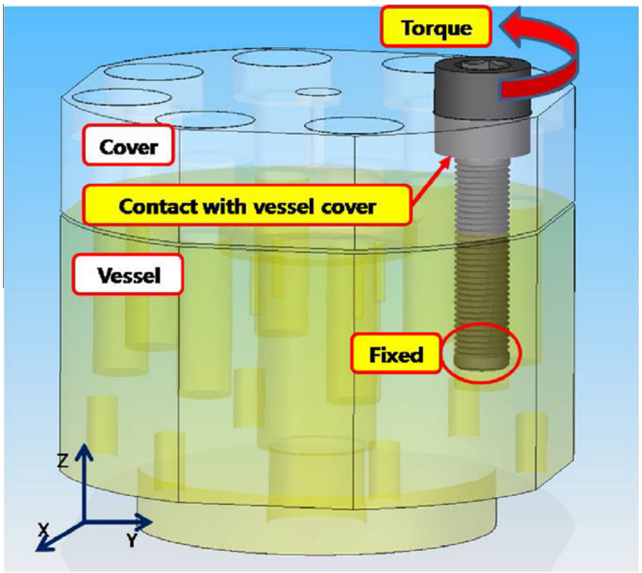


**Fig. 8.** FE model of the pressure vessel bolt with considering loose parts in the thread hole.

## 4. Stress analysis

In order to analyze the stress distribution of the pressure vessel bolt, the FE model with 14 mm in diameter and 77 mm in length was created by using the commercial 3D modeler, SolidEdge V19 as shown in Fig. 8. The end region of the constrained

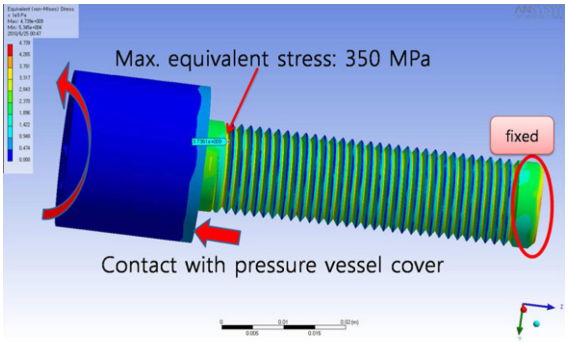


**Fig. 9.** Model of Von-Mises stress distribution in the pressure vessel bolt.

bolt where loose parts are contacted is fixed and the torque of 60 N m is applied on the bolt head. The FE model consisted of about 28,900 nodes and 16,200 elements. The material properties used in this analysis such as elastic modulus, yield strength, density and Poisson's ratio of commercial SUS 440C are listed in Table. 2. The commercial code, ANSYS® Workbench V10.0, was used to post-process the model in order to calculate the Von-Mises stress exerted on the bolt. The Von-Mises stress distribution in the pressure vessel bolt showed that the high stress concentrations were appeared at the neck region of the bolt as shown in Fig. 9. In particular, the maximum stress was approximately 350 MPa and this value is about a quarter of the yield stress of the failed bolt even though the thermal stress due to the temperature change and the contact condition between the bolt head and the autoclave cover were not considered in this analysis. Therefore, the failure position of the pressure vessel bolt is in good accord with the FE analysis result. Consequently, the faulted heat treatment condition and loose parts in the thread hole of the autoclave played major role of the bolt fracture. Based on this result, the bolt material was changed to austenite stainless steel in order to increase the fracture toughness and the thread hole of the autoclave is always cleaned before each fretting wear test.

## 5. Summary

In order to investigate the failure reason of the pressure vessel bolt in the fretting wear simulator, a measurement of the micro-vickers hardness, a tensile test with the fractured bolt, SEM observations and a finite element analysis were used and the following conclusions can be summarized:

(1) The fracture surface shows the intergranular morphologies but has no evidence of fatigue failure. Also, it is difficult to explain the bolt failure with the exerted tensile stress on each bolt generated by internal pressure.
(2) Based on the results of the micro-vikers hardness and tensile test with the failed bolt, it is confirmed that the failed bolt was fully hardened by the faulted surface hardening condition.
(3) Due to the loose parts in the thread hole, it is possible to generate the excess stress induced by the torque during fastening. Also, the stress concentration region of the FE analysis results corresponded well with the bolt failure.
(4) It is recommended that the bolt material is changed to austenite stainless steel in order to increase the fracture toughness and the thread hole of the autoclave is always cleaned before each fretting wear test.

## Acknowledgement

This study has been carried out under the Nuclear R&D Program by Ministry of Science and Technology in Korea.

## References

[1] Kim HK, Lee YH, Ryew SM, Kim CH, Kim MH. Development of vertical type high temperature and pressure fretting wear tester (FRETONUS). In: Proceedings of KSTLE spring meeting; 2008.
[2] Fisher NJ, Weckwerth MK, Grandison DAE, Cotnam BM. Fretting-wear of zirconium alloy. Nucl Eng Des 2002;213:79–90.
[3] Ojima M, Ohnuma M, Suzuki J, Ueta S, Narita S, Shimizu T, et al. Origin of the enhanced hardness of a tempered high-nitrogen martensitic steel. Scripta Materialia 2008;59:313–6.
[4] Davis JR. ASM specialty handbook – Stainless steels; 1996.