DESIGN RELATED FAILURE OF THERMOWELLS IN FEED GAS SUPPLY DOWNSTREAM PIPELINE

A. El-Batahgy[1], *G. Fathy*[2], *M. Amin*[1]
[1]*Central Metallurgical R & D Institute, Cairo, Egypt;* [2]*Natural Gas Production Company, Cairo, Egypt*

Abstract

After only one year of operation, thermowells in feed gas supply pipeline at a natural gas production plant was failed due to fatigue damage accelerated by improper thermowell design for the current operation. It is believed that thermowell configuration having a neck acted as local stress raiser played a remarkable role in initiation of fatigue damage. Besides, the medium flow past a thermowell causes vortices to be shed at a frequency, termed the wake frequency, proportional to the flow velocity. If the wake frequency is at or near the natural frequency of thermowell, a resonance condition may occur where massive amounts of energy are absorbed by the thermowell, resulting in very high stresses and possible failure.

The problem was solved by using modified thermowell configuration to minimize both stress concentration and resonance. In this regard, a thermowell having a continuous low-gradient slope (truncated conical-type thermowell) was used since it has a higher natural frequency and a lower stress concentration in comparison with the failed one that was flanged, straight type thermowell.

1. Introduction

A natural gas production field has been set into operation about six years ago. Natural gas produced from the well is processed through different stages before being supplied through pipelines for local market or export. Temperatures of the gas during its different processing and supplying stages are being monitored using thermowells. Some of thermowells have been installed one year ago at the feed gas supply downstream pipeline to monitor temperature. Flanged, straight type thermowells made of 316 stainless steel are fixed in a vertical position on the top of 30inch diameter pipelines where its flange is about 20cm above top of pipeline. The thermowell consists of a tube connected to a flange by a sloped neck. The tube outer diameter, thickness and length are 19mm, 6.5mm, 260mm, while flange diameter and thickness are 155mm and 23mm respectively.

Actual operating conditions are as follows:

Characteristics	Minimum	Maximum
Flow rate, MMSCFD	700	1100
Pressure, bar	75	85
Temperature, ^{o}C	12	28
Maximum gas velocity, m/sec	12.4	
Gas specific gravity	0.568	
Gas density, g/l	0.6952	

After such short service period (one year), leakage has occurred as a result of failure of thermowells.

2. Investigation

Failed thermowells were subjected to different non-destructive and destructive tests including visual investigation, dimensions measurement, liquid penetrant test, stereoscopic examination, chemical analysis, optical and scanning electron microscopic examinations, and hardness measurements. General and enlarged views of one of several failed thermowells are shown in Fig. 1. One important notice is that thermowell was circumferentially cracked at the neck of tube with flange. It can be noticed that the outer surface of the failed thermowell is clean and free from deposits or indications for corrosion. Dye penetrant inspection indicated no surface cracks either around or away from fractured zone of thermowells.

Enlarged views of cracked thermowell during and after separation of the remainder of its circumference are shown in Fig. 2. Crack initiation zone is highlighted with arrows. Visual examination showed that thermowell had cracked along neck between flange and tube. The crack extended more than half way around the circumference of the neck. The remainder of the circumference had been separated gradually with hand. It was not clear whether the crack originally extended more than half way around the circumference, or whether it had been shorter but part of it was extended by mishandling of thermowell during or after removing it from its location on pipeline. However, it is clear that crack was started at outer surface of thermowell neck which is considered as stress concentration zone.

Stereoscopic photograph of fractured or cracked surface of thermowell is shown in Fig. 3. It is obvious that fracture was initiated at outer surface of thermowell tube' neck where smooth fracture surface can be seen. Approximately 80% of the fracture surface appeared relatively smooth and associated with beach marks of a propagating ductile crack. The remaining 20% of the surface had a rough texture associated with the final brittle fracture of the thermowell. Beach marks, crack initiation sites on outer surface and propagation directions are highlighted with arrows.

Generally, internal surface of thermowell tube showed smooth surface with no indications for internal corrosion. In other words, no thinning or variation in tube wall thickness was observed where uniform wall thickness (6.5mm) was obtained at both fractured and non-fractured zones.

Specimens from both failed and non-failed zones of the received thermowells were cut out and prepared for chemical analysis, metallographic examination, and hardness measurements. Result of chemical analysis of failed thermowell together with the specified chemical composition range for type 316 stainless steel are shown in Table 1. It is obvious that chemical composition of the used thermowell is a typical for austenitic stainless steel type 316.

Optical micrographs with different magnifications of as-polished cross section taken from fractured zone (thermowell neck) are shown in Fig. 4 while those of as-polished cross section taken away from fractured zone are shown in Fig. 5. The most important notice is the existence of second phase in the austenitic matrix of failed thermowells.

Optical micrographs of etched cross section, taken from fractured zone (thermowell neck) are shown in Fig. 6 while those of etched cross section taken away from fractured zone are shown in Fig. 7. For both cross sections, no micro-cracks were found. Similar microstructure was obtained for both specimens taken close to and away from fractured zone. No microstructural difference was obtained between outer surface, through thickness and inner surface of investigated specimens. All specimens showed austenitic microstructure with second phase precipitates within matrix.

Survey of hardness measurements indicated almost same hardness values at both fractured and non-fractured zones where average hardness values of 187HV and 179HV were obtained for fractured and non-fractured zones respectively. High hardness value (~300HV) was obtained for second phase compared with that of the matrix (185HV).

In order to help in identification of failure mechanism, cracked or fractured surface including suspected initiation zone was investigated using scanning electron microscope. It is confirmed that initiation sites are confined to thermowell tube outer surface just at thermowell neck where stress concentration sites were existed. Scanning electron micrographs with different magnifications of fracture suspected initiation sites at neck outer surface are shown in Fig. 8 while those of fracture surface away from initiation zone are shown in Fig. 9.

Crack initiation sites can be seen on outer surface of thermowell neck where a single macroscopic direction of crack propagation is impossible to be defined. This is because crack size is still in the microcrack zone, where multiple cracks form at the surface, initiating at different locations and with different orientations (Fig. 8). The important notice is the fatigue striations at fracture initiation zone on neck outer surface. On the other hand, brittle fracture was observed away from fracture initiation zone or neck inner surface as shown in Fig. 9.

3. Discussion

Visual and macroscopic examinations of the failed thermowells showed that the fractured zone was confined only to thermowell neck where cracks were propagated from outer surface into inner surface in two opposite directions along tube circumference. No indications for corrosion attack were observed. It was not clear whether the crack originally extended more than half way around the circumference of thermowell neck, or whether it had been shorter but part of it was extended by mishandling during or after removing thermowell. However, it is clear that crack was started at outer surface of thermowell neck which is considered as stress concentration zone.

Stereoscopic examination of fracture surface of failed thermowell indicated beach marks. Scanning electron microscopic investigation of fracture surface showed fatigue striations at fracture initiation zones. These findings support fatigue as a failure mechanism. Based on chemical analysis of failed thermowell, its material was found to be within the specification of type 316 austenitic stainless steel. However, its microstructure included second phase particles with higher hardness than the austenitic matrix at both failed and non-failed zones.

Fatigue failure is the phenomenon leading to fracture under repeated or fluctuating stresses that are less than the tensile strength of the material. Fatigue fractures are progressive, beginning as minute cracks that grow under the action of fluctuating stress. There are three stages of fatigue failure: initiation, propagation, and final fracture. The initiation site is minute, never extending for more than two to five grains around the origin. The location of the initiation is at a stress concentration. It is believed that thermowell neck that acts as local stress raiser played a remarkable role in fatigue failure [1-4]. In other words, thermowell neck worked as site for initiation of fatigue damage on its outer surface.

A cyclic stress could have been applied due to pressure surges, pressure pulses, and/or overpressure stresses. Generally, thermowells are subjected to more than just the static forces from the medium going past. They can also have vibrations induced from the medium vortices in the wakes created by the interaction between them and the medium. This is most significant in the realm of highly energetic flows. The induced vibrations are very critical when their frequency corresponds to the resonance frequency of a thermowell. Under such conditions, not only the temperature sensors can literally be pounded to pieces but also thermowells themselves can rupture in extreme cases. In other words, medium flow past a thermowell causes vortices to be shed at a frequency, termed the wake frequency, proportional to the flow velocity. If the wake frequency is at or near the natural frequency of thermowell, a resonance condition may occur where massive amounts of energy are absorbed by the thermowell, resulting in very high stresses and possible failure.

After the original fatigue crack is formed, it becomes an extremely sharp stress concentration that tends to drive the crack ever deeper into the metal with each repeating of the stress. The local stress at the tip of the crack is extremely high because of the sharp “notch,” and with each crack opening, the depth of the crack advances by one “striation”. Striations are very tiny, closely spaced ridges that identify the tip of the crack at some point in time [5, 6].

Whenever there is an interruption in the propagation of a fatigue fracture a unique feature of macroscopically visible marks or ridges may be found. These marks are described as “beachmarks” or “growth rings”. Figure 3 shows an example of beachmarks in the subject fatigue failure. Beachmarks must not be confused with striations, although they frequently are present on the same fracture surface; there may be many thousands of microscopic striations between each pair of macroscopic beachmarks. As the propagation of the fatigue crack continues, gradually reducing the cross-sectional area, it eventually weakens the material so greatly that final, complete fracture occurs [7, 8].

Conclusions and Recommendations

Based on the results obtained in this investigation, it can be concluded that the premature failure of thermowells is attributed to fatigue damage due to improper thermowell design for the current application. High stress concentration at thermowell neck and flow-induced vibration, both have shortens the lifetime of the used flanged, straight type thermowell.

Fatigue failure is the phenomenon leading to fracture under repeated or fluctuating stresses that are less than the tensile strength of the material. The initiation site of fatigue failure is minute, never extending for more than two to five grains around the origin. The location of the initiation is at a stress concentration. It is believed that thermowell neck that acts as local stress raiser played a remarkable role in initiation of fatigue damage on its outer surface.

This failure could be accelerated by pressure surges, pressure pulses, and/or overpressure stresses. The medium flow past a thermowell causes vortices to be shed at a frequency, termed the wake frequency, proportional to the flow velocity. If the wake frequency is at or near the natural frequency of thermowell, a resonance condition may occur where massive amounts of energy are absorbed by the thermowell, resulting in very high stresses leading to failure.

It is obvious that the fracture initiated at outer surface of thermowell neck and propagated across the neck in two opposite directions. As the propagation of the fatigue crack continues, gradually reducing the cross-sectional area, it eventually weakens the material so greatly that final, complete fracture occurs.

In order to avoid such failure in future, thermowell shape or configuration was modified to minimize both stress concentration and resonance. To minimize resonance between gas flow and the thermowell, the natural vibration of thermowell must be designed so as to avoid the range of flow-induced vibrations. In this regard, a thermowell having a continuous low-gradient slope (truncated conical-type thermowell) was used since it is structurally stronger than the failed one that was flanged, straight type. In other words, the newly selected truncated cone shape thermowell type has a higher natural frequency and a lower stress concentration in comparison with the failed one.

References

[1] El-Batahgy A. Influence of HAZ and stress concentration on fatigue strength of welded structural steel, Materials Letters 21 (1994) 45-52.
[2] El-Batahgy A and Metwally W. Weld defect and design induced failure of draught fan of boiler flow gases”, Al-Azhar Engineering Fifth International Conference, 19-22 February 1997, Cairo
[3] El-Batahgy. A and Zaghloul B. Fatigue failure of off shore condensate recycle line of production separator at natural gas production field, International Conference on Fracture ICF 11, 20-25 March 2005, Turin, Italy.

[4] A. El-Batahgy and M. Abdalla: "Catastrophic failure of HP steam transferring pipeline of a newly erected boiler", Doc. X1601-06, Annual Assembly of IIW, Quebec, Canada, Aug. 27-Sept.2, 2006.
[5] Barer RD and Peters BF. Why Metals Fail, 6th ed., Gordon and Breach, Science Publishers, New York, 1991.
[6] ASM Handbook, Failure Analysis and Prevention, Vol. 11, Materials Park, OH: ASM International, 1996.
[7] Colangelo VJ, Heiser FA. Analysis of Metallurgical Failures, 2nd. ed., New York, NY: Wiley, 1987.
[8] Brooks CR, Choudhury A. Metallurgical Failure Analysis, McGraw-Hill, New York, 1993.

Table 1. Results of chemical analysis (wt%) of the used thermowell together with the specified chemical composition range for 316 stainless steel.

Material	**C**	**Si**	**Mn**	**S**	**P**	**Cr**	**Ni**	**Mo**
Failed thermowell	0.03	0.38	1.99	0.004	0.026	18.00	10.04	2.1
316 St. St.	<= 0.08	<= 1.0	<= 2.0	<= 0.03	<= 0.04	16.0~ 19.0	9.0~ 12.0	2.0 ~ 3.0

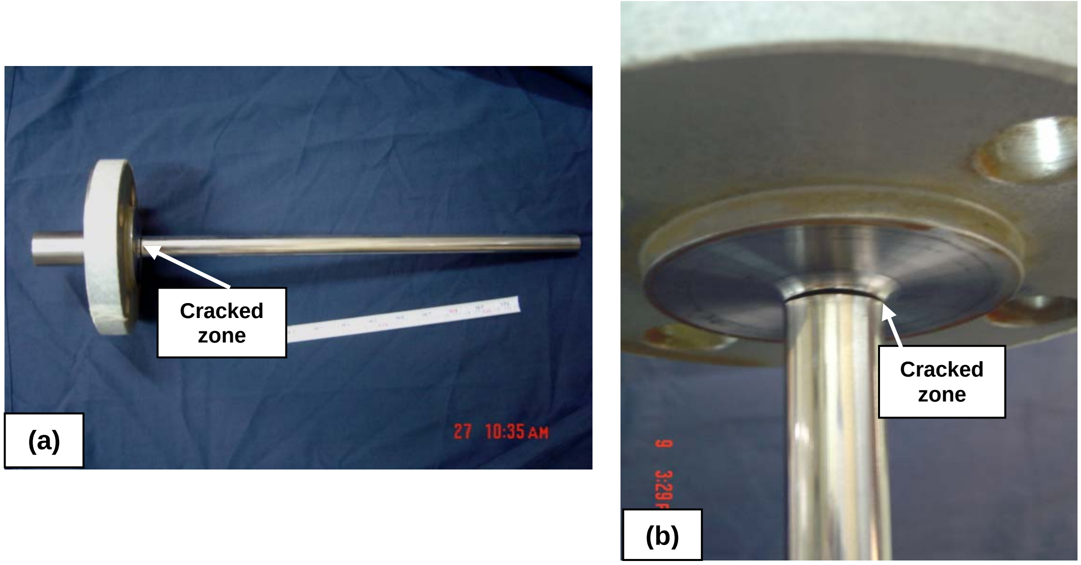

Fig. 1. General (a) and enlarged (b) views of one of several racked thermowells. Note that crack had occurred at the neck between flange and tube.

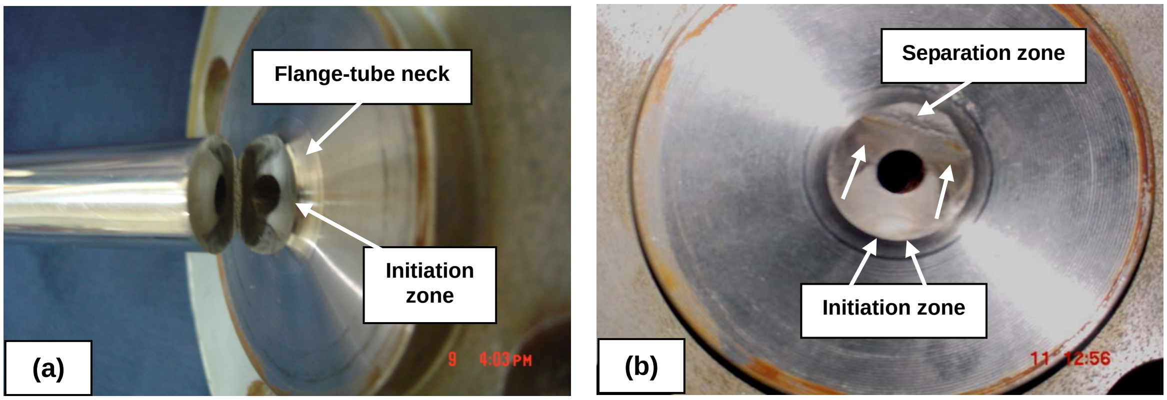

Fig. 2. Enlarged views of cracked thermowell during (a) and after (b) separation of the remainder of its circumference. Crack initiation zone is highlighted with arrows.

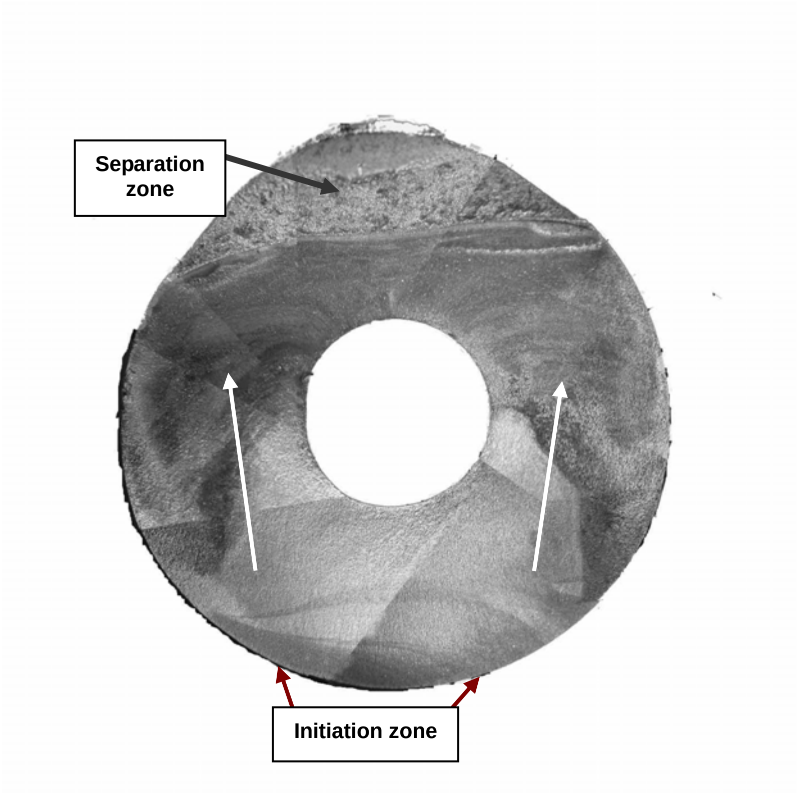

Fig. 3. Stereoscopic photograph of fractured or cracked surface of thermowell. Beach marks, crack initiation zone and fracture propagation direction are highlighted with arrows.

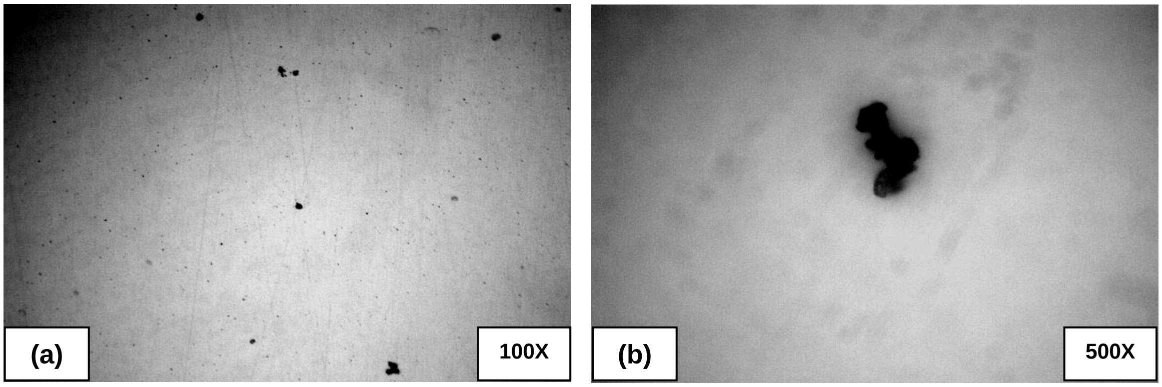

Fig. 4. As-polished optical micrographs of a cross section from fractured zone (thermowell neck).

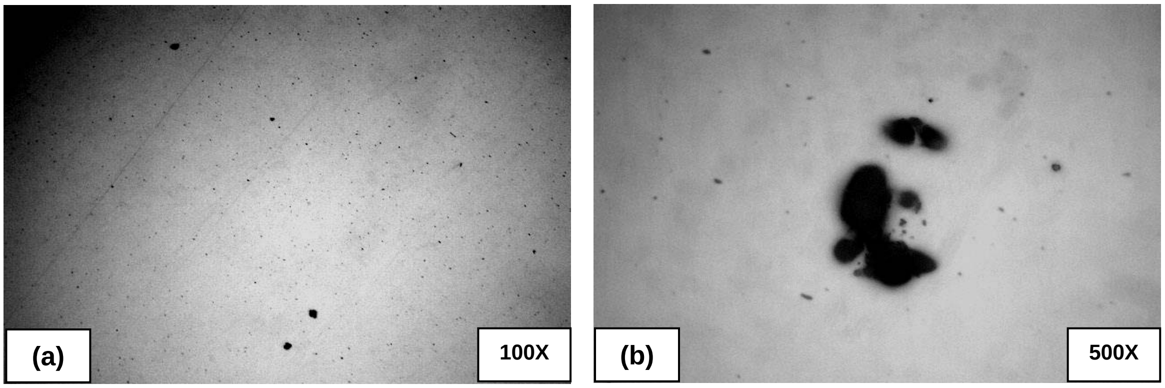

Fig. 5. As-polished optical micrographs of a cross section taken away from fractured zone.

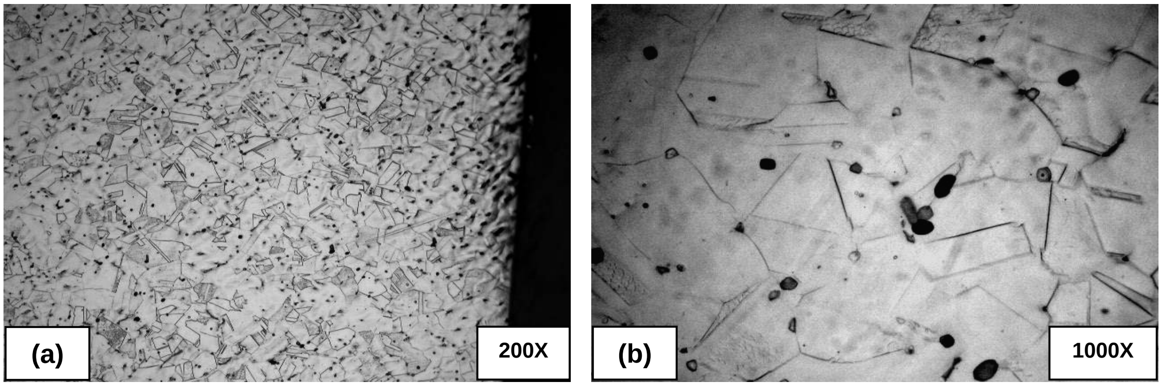

Fig. 6. Etched optical micrographs of a cross section taken from fractured zone (thermowell neck).

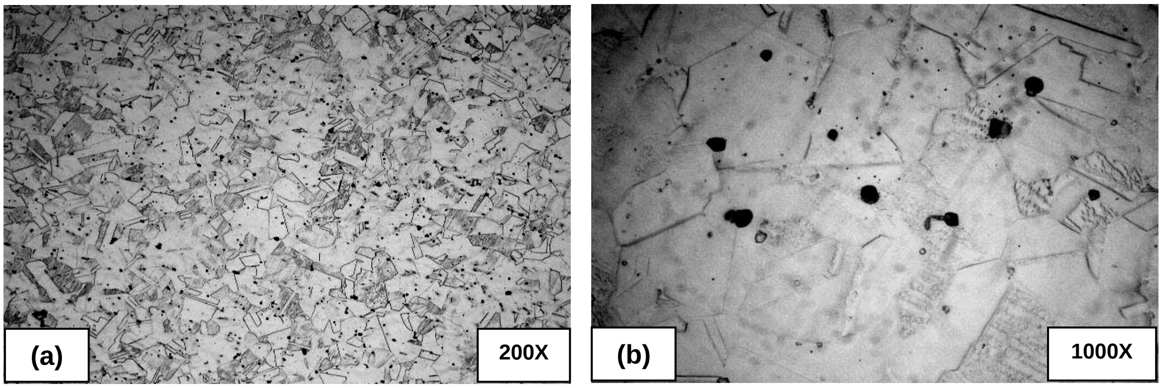

Fig. 7. Etched optical micrographs of a cross section taken away from fractured zone.

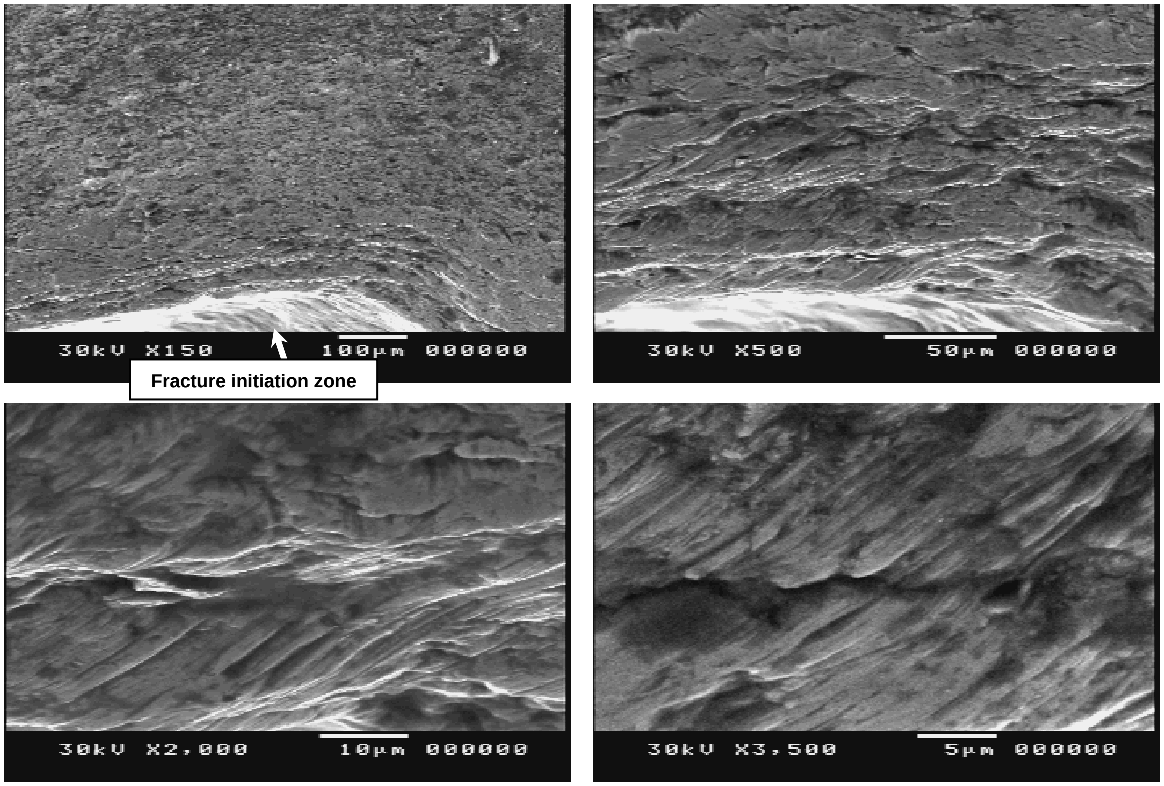

Fig. 8. Scanning electron microscopic photographs of fracture suspected initiation zone at neck outer surface showing fatigue striations.

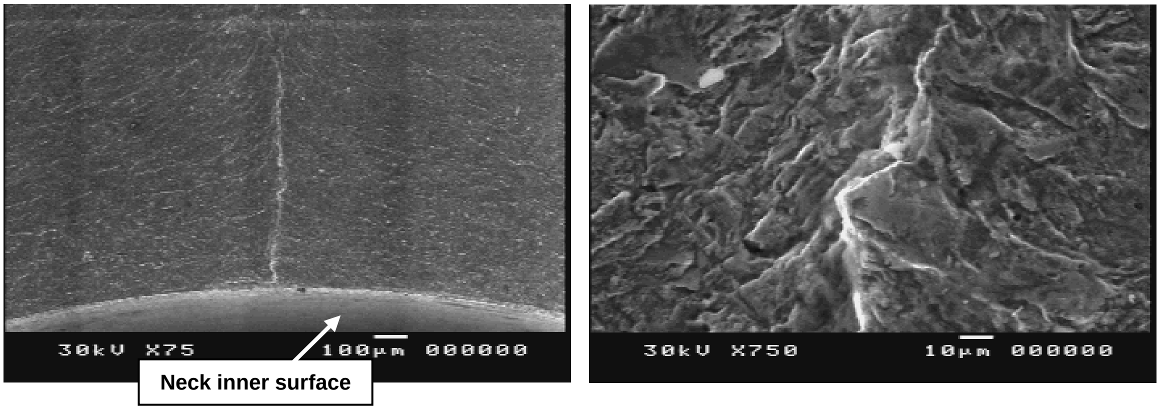

Fig. 9. Scanning electron microscopic photographs of fracture termination zone (neck inner surface), showing brittle fracture.