



## FATIGUE FAILURE IN A LONGITUDINAL WELDED ELBOW OF A PROCESSING VESSEL

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### Abstrak

Belokan (*elbow*) dengan las memanjang yang terbuat dari baja tahan karat austenitik tipe 316 dan digunakan sebagai saluran pembuangan (*drain*) pada bejana pengolahan telah mengalami kebocoran setelah baru beroperasi beberapa tahun. Fluida proses yang dikuras keluar dari bejana terdiri dari cairan asam lemak yang mengandung gas hidrogen pada suhu 150 °C dan tekanan 60 bar. Awalnya proses drain hanya dilakukan setahun sekali, namun belakangan karena seringnya terjadi perubahan jenis produk yang dibuat, frekuensi proses drain meningkat menjadi beberapa kali dalam sebulan. Penelitian ini bertujuan untuk mengetahui jenis dan faktor penyebab terjadinya kebocoran pada belokan. Asesmen metalurgi dilakukan dengan menyiapkan sejumlah benda uji dari belokan yang bocor. Sejumlah pemeriksaan laboratorium telah dilakukan meliputi uji visual dan makroskopik, analisis komposisi kimia, pemeriksaan metalografi, uji kekerasan dan SEM (*scanning electron microscope*) yang dilengkapi dengan analisis EDS (*energy-dispersive spectroscope*). Hasil yang diperoleh menunjukkan bahwa belokan yang bocor tersebut telah mengalami kegagalan fatik akibat pembebanan siklik yang disebabkan oleh meningkatnya frekuensi jumlah proses drain yang dilakukan melalui belokan tersebut. Faktor penyebab kegagalan fatik pada belokan kemungkinan disebabkan oleh cacat las berupa bentuk tidak sempurna (*imperfect shape*) akibat tonjolan logam las (*weld overlap*) pada dinding bagian dalam belokan di sekitar HAZ (*heat-affected zone*)/batas fusi dan menimbulkan konsentrasi tegangan yang tinggi di daerah itu.

**Kata Kunci:** Belokan dengan las memanjang, kegagalan fatik, cacat las bentuk tidak sempurna, batas fusi, konsentrasi tegangan

### Abstract

*Longitudinally welded elbow made of austenitic stainless steel type 316 and used as a drain line on a processing vessel had suffered damage (leakage) after it had only been in operation for a few years. Process fluid that was drained out of the vessel consists of fatty acid-containing hydrogen gas at a temperature of 150 °C and a pressure of 60 bar(g). Initially, the draining process was carried out only once a year, but recently due to frequent changes in the types of product being made, the frequency of the draining process has increased to several times a month. This study aims to determine the type and factors that have caused leakage in the elbow. The metallurgical assessment was carried out by preparing many specimens from the leaking elbow. A number of laboratory examinations were performed, including visual and macroscopic tests, chemical composition analysis, metallographic examination, hardness tests, and SEM (scanning electron microscope) equipped with EDS (energy-dispersive spectroscope) analysis. The results obtained indicate that the leaking elbow has experienced fatigue failure due to cyclic loadings caused by the increasing frequency of drain processes carried out through the elbow. The factor causing fatigue failure at the elbow is likely caused by welding defect due to poor shape (weld overlap) that formed on the inner wall of the elbow around the HAZ (heat-affected zone)/fusion boundary and causing high-stress concentrations in that area.*

**Keywords:** Longitudinal welded elbow, fatigue failure, imperfect shape weld defect, HAZ (heat-affected zone)/fusion boundary, stress concentration

## 1. INTRODUCTION

Fatigue failures generally occur in rotating equipment components due to load cycles such as pumps, compressors, turbines and others [1]-[8]. In addition, fatigue failures can also occur in stationary equipment such as piping, pressure vessels, heat exchangers, elbows, and others that experience fluctuating internal pressures [9]-[12] or due to flow-induced vibrations [13]-[14]. Although the operating load is still within the elastic range or below the yield strength of the material, however due to repeated loading conditions, local plastic deformation can occur in component area experiencing high stress concentration so that after certain operating time passed away it will cause initial cracks. In the continuation of the operation, the cracks then propagate and grow to form a pattern like beach marks with a topology of smooth cracks or fractures surface due to the rubbing effect that occurs. In the final stage when the remaining cross-sectional area of the component is no longer able to accept the working load, the component will experience a final fracture, or in case of pressurized components when the crack can penetrate the component wall and cause leakage. The fracture surface topology that occurs in component areas that experience final fracture generally shows a relatively coarser pattern when compared to component areas that experience crack propagation or beach marks. The crack pattern in the final fracture area can be ductile or brittle, depending on the type of material and loading conditions. If the signs of beach mark formation are not clearly visible, the fatigue crack propagation can be identified by formation of striations using SEM fractographs [15]-[16]. Meanwhile, in areas with final fractures, SEM fractographs usually exhibit dimple pattern in case of ductile fractures or chevron markings (or cleavage) pattern in case of brittle fractures [1]-[3].

Depending on the load and environmental conditions, fatigue failures can be classified as mechanical fatigue, thermal fatigue, and corrosion fatigue. Failures due to mechanical fatigue is mainly caused by mechanical load cycles [1]-[5], while thermal fatigue is caused by thermal load cycles due to temperature fluctuations and/or temperature gradients that occur in components [7]-[8]. Furthermore, for corrosion fatigue, formation of some localized corrosion such as pitting, fretting, cavitation, etc., may contribute and precede the fatigue failure [17]. Generally, fatigue failures can be resulted from several factors such as design, material,

manufacturing/fabrication, operation and maintenance [2], [5].

In this study, the fatigue failure occurred in the longitudinal welded elbow that was installed and used as a drain line in a processing vessel has been studied and discussed related to the factors that cause leakage in the elbow. The objective of the study is to verify the material properties and to determine whether the material used for the elbow meet the specification or suitable for its operating condition. Furthermore, the aim of the study is to establish the type, cause and mode of failure of the elbow, and based on the determination, some corrective or remedial action may be initiated that will prevent similar failure in the future.

## 2. MATERIALS AND METHODS

The leaking elbow as shown in Figure 1, having outside diameter of 2" was made of austenitic stainless steel 316 type. The elbow was used as a drain line of fatty acid fluid containing hydrogen gas out of a processing vessel. The elbow and its processing vessel were operated at maximum temperature of 150°C and under a pressure of 60 bar(g). According to the plant information, the drain process was initially carried out approximately once a year, but recently due to changes in the types of products made, the drain process has increased several times a month.

In this study, the leaking elbow shown in Figure 1 was cut into a number of specimens for laboratory examination. Macroscopic examination on the fracture surface of the leaking elbow was performed using a stereomicroscope. Chemical analysis on the prepared sample was carried out using optical spark emission spectrometer. The purpose of this chemical analysis was to determine whether the material used for the leaking elbow met the specification. In addition, metallographic examinations were also performed on the prepared samples using an optical microscope at various magnifications. The metallographic samples were mounted using epoxy and prepared by grinding, polishing and etching. The etchant applied was aqua-regia solution [17]. A hardness survey was also carried out on the same samples for the metallographic examination using the Vickers hardness method at a load of 5kg (HV5). Moreover, examination of some fracture surface of the leaking elbow sample was also performed using scanning electron microscopy (SEM) to determine the fracture surface topography and nature of the failure. This SEM was also equipped with an

energy dispersive spectroscopy (EDS) analysis to detect the presence of any corrosion by-product.

### 3. RESULTS AND DISCUSSIONS

#### 3.1 Visual and Macroscopic Examination

In order to determine the location of the leak, the damaged elbow as shown in Figure 1 was cut-off into two halves. Figures 2 and 3 show one of the elbow halves showing the inside of the elbow. From Figures 2 and 3 it can be seen that the leaking elbow was actually made of a longitudinally welded tube and the leakage was caused by some longitudinal crack formed in the area around the longitudinal weld located between the weld metal (WM) and the heat-affected zone (HAZ), or around the fusion boundary.

The fracture surface obtained along the crack path of the elbow as shown in Figures 2 and 3 is presented in Figure 4. According to the crack topography and damage pattern, the cracked elbow as shown in Figure 4 is presumed to have suffered a fatigue fracture. This fatigue fracture is characterized by the formation of smooth beach marks [1]-[2], [17] on almost the entire fracture surface of the elbow section. Fatigue cracks can be seen clearly starting from the weld defect of imperfect shape due to weld overlap formed on the inner wall of the elbow where a high stress concentration may present.

Prior to the fatigue crack approaches the OD side of the elbow, the crack grows very rapidly and penetrates the remainder of the cross section causing a leak in the elbow. The rough fracture surface left by the fast crack is the final fracture. It can be seen from the fatigue fracture surface shown in Figure 4 that the final fracture surface area is relatively smaller than the crack propagation (beach marks) area. This suggested that the fatigue fracture of the failed elbow was produced by a low nominal stress, but under an abnormal high or severe stress concentration [17]. The low nominal stress indicated that the elbow material located around the cracked area was subjected to a low and normal loading condition during its operation, whereas the severe stress concentration was most likely taking place on the internal wall of the elbow where the weld defect due to imperfect shape present. Formation of weld defect was likely as the result of weld metal overlap occurred during elbow fabrication and could generate a high tensile stress concentration and initiated the fatigue crack. The cyclic loadings that may result in fatigue cracking at the elbow were likely affected by the frequent removal of the fatty acid liquid containing hydrogen gas out of the vessel.



Figure 1. As-received elbow for laboratory examination, showing a longitudinal line mark formed at the leakage location

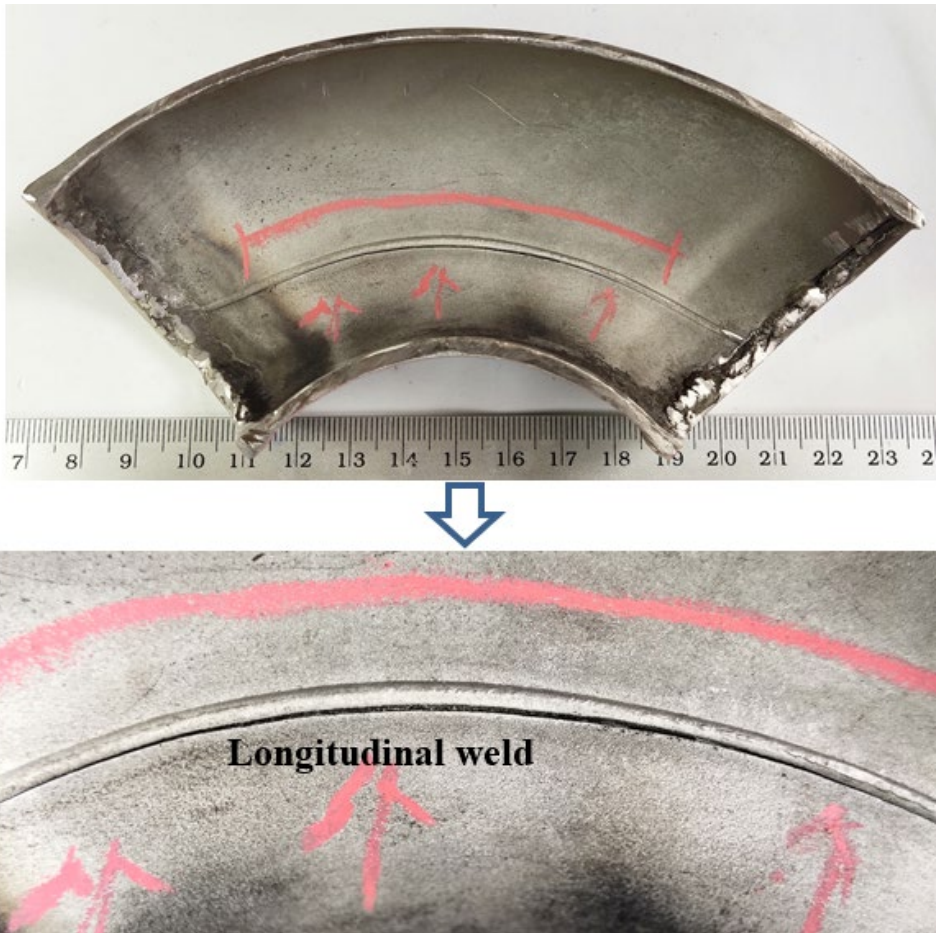


Figure 2. Close-up view at the internal surface after cutting the elbow into two halves showing a longitudinal weld that had been applied for fabricating the elbow

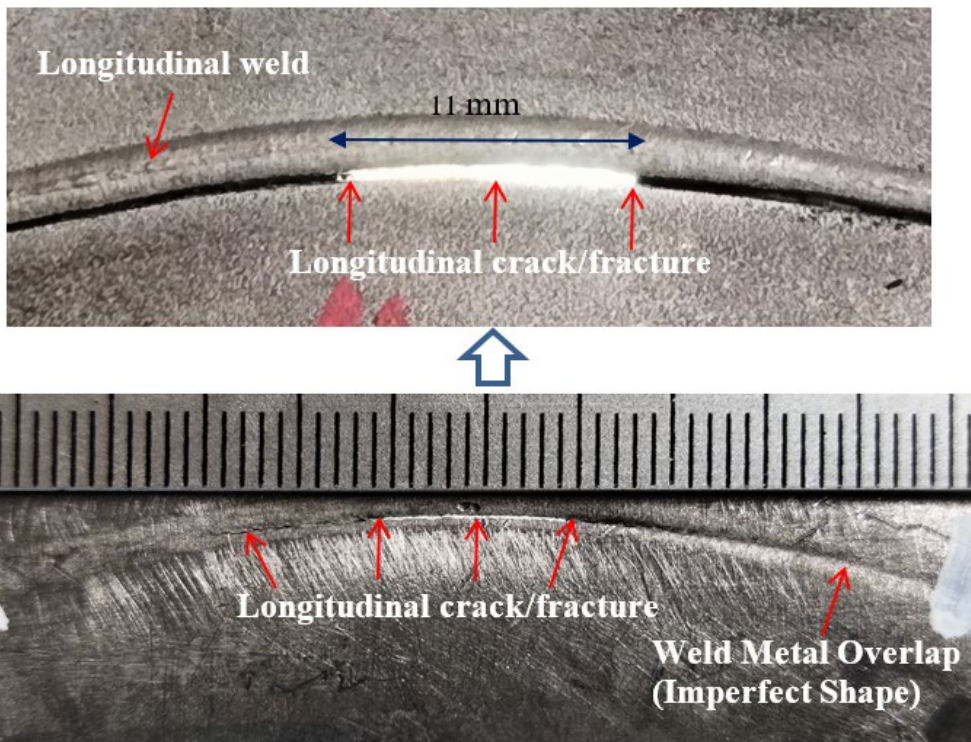


Figure 3. Close-up view of some internal wall of the elbow at leakage location revealing a crack or fracture in the longitudinal direction at the HAZ/fusion boundary of the longitudinal weld

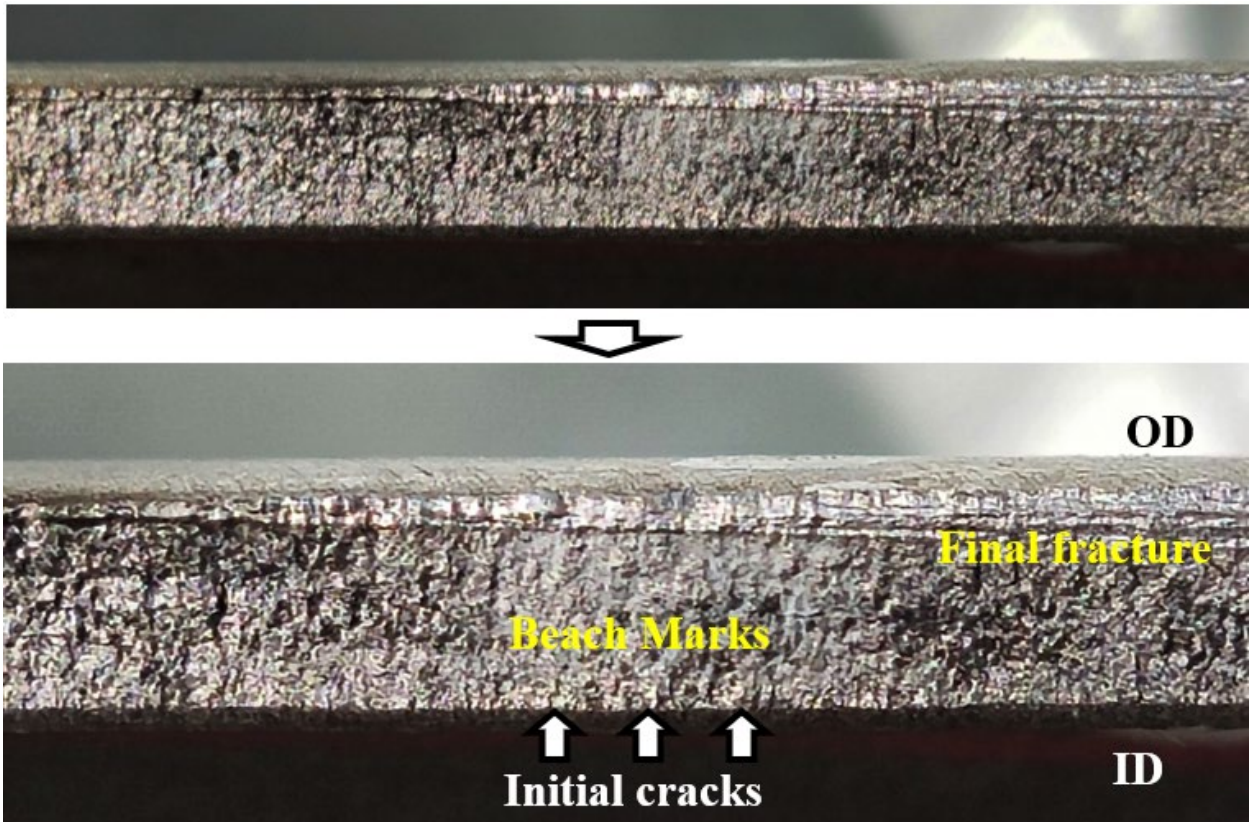


Figure 4. Low-magnification view of fracture surface of the leaking elbow pointing toward crack initiation from ID surface as well as beach marks and the final fracture at the OD side

Table 1. Results of chemical analysis obtained from the damaged elbow material in comparison with the standard material of AISI type 316 austenitic stainless steel

Element	Composition, Wt-%	
	Damaged Elbow Material	Standard Material (AISI type 316)
Fe	66.79	Balance
C	0.056	0.08 (max)
Si	0.741	1.00 (max)
Mn	1.482	2.00 (max)
P	0.026	0.045 (max)
S	0.011	0.03 (max)
Cr	17.20	16.00 - 18.00
Ni	10.85	10.00 - 14.00
Mo	2.270	2.00 - 3.00
Cu	0.189	-
V	0.083	-
Nb	0.023	-
Al	0.028	-
Ti	0.015	-
Co	0.215	-
W	0.021	-

### 3.2 Chemical Analysis

From the results of chemical analysis obtained on the damaged elbow material, it was found that the material used for the elbow was

completely met to the material specification of AISI type 316 austenitic stainless steel, see Table 1. This indicates that the material factor is not expected to contribute to the occurrence of

damage to the elbow. In addition, the selection of austenitic stainless steels used in elbow is considered adequate for hydrogen gas-containing environments in order to avoid possible hydrogen embrittlement.

### 3.3 Metallographic Examination and Analysis

For metallographic examination, two specimens were made from the damaged elbow. First specimen marked as A was located within the leaking area cut in tangential direction and prepared parallel to the elbow surface. The second specimen marked as B was obtained from location where the crack has not completely penetrated the elbow's wall thickness and prepared in transverse section.

The macrostructure and microstructures obtained from specimen A are presented in Figure 5, showing the different examination areas including the initial fatigue crack area occurring at the HAZ/fusion boundary of the weld defect, fatigue crack path or fracture surface, final fracture and secondary fracture area. The microstructures obtained consisted of all austenitic phase matrix with several twin boundaries, typical of AISI type 316 austenitic stainless steel. Figure 5 also shows that fatigue crack origins occur on the elbow's ID surface at a location between WM and HAZ or around the fusion boundary. In this area, it is clearly seen that there is some weld defect in the form of discontinuity or imperfect shape due to weld

overlap. It is estimated that in this area a high stress concentration may be present so that it can initiate the occurrence of fatigue cracks. The fatigue crack then propagates toward the OD side of the elbow forming a more or less straight path in transgranular manner and unbranched, typical of fatigue crack mechanism. Further from Figure 5 it is found that secondary fatigue cracks have also formed in the area around the fusion boundary between WM and HAZ at other location nearby the WM bead area.

Macrostructure and microstructures obtained from specimen B at location outside of the leaking area of the elbow are presented in Figure 6. The microstructures obtained were all similar to that obtained from specimen A, consisting of austenitic phase matrix with several twin boundaries

Similarly, fatigue cracks can also be seen starting from the inner wall of the elbow, namely from a weld defect formed at the HAZ/ fusion boundary which is located between HAZ and WM. Fatigue crack propagation toward the OD side appears to form a more or less straight path in transgranular manner without crack branching. However, from Figure 6 it can be seen that the secondary fatigue crack that observed in specimen A has not formed in specimen B. From Figures 5 and 6, it apparently shows that the cracks propagated in transgranular manner typical of fatigue failure.

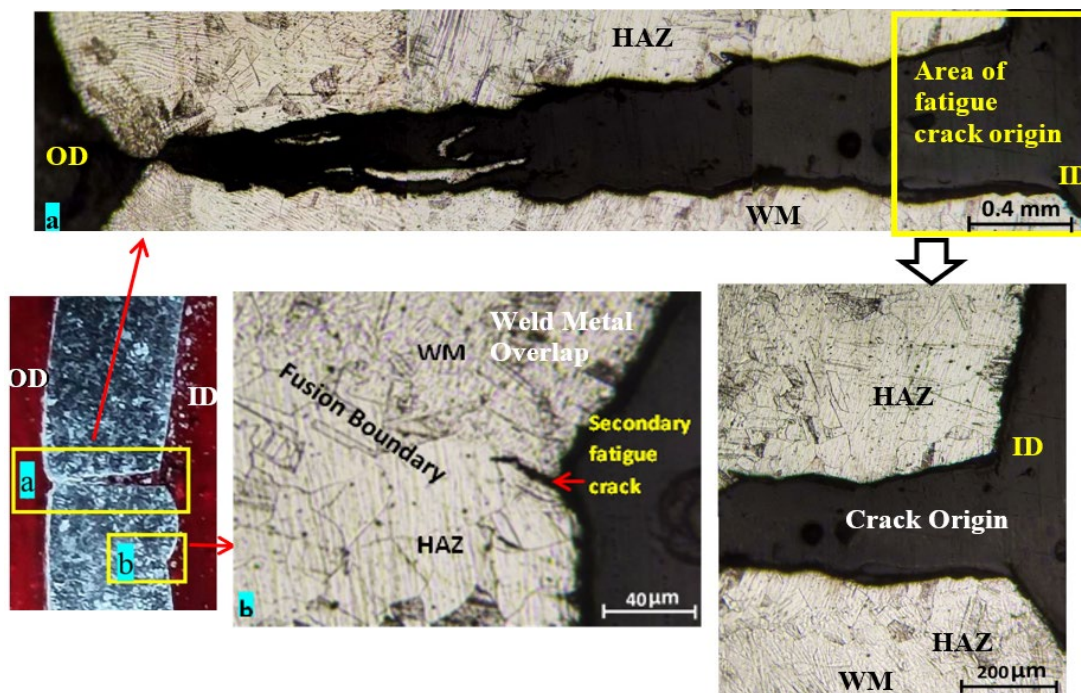


Figure 5. Macrostructure and microstructures of specimen A obtained from the leaking area showing one of the fatigue cracks that had penetrated through the elbow's wall thickness to cause leakage (etched by aqua-regia solution)

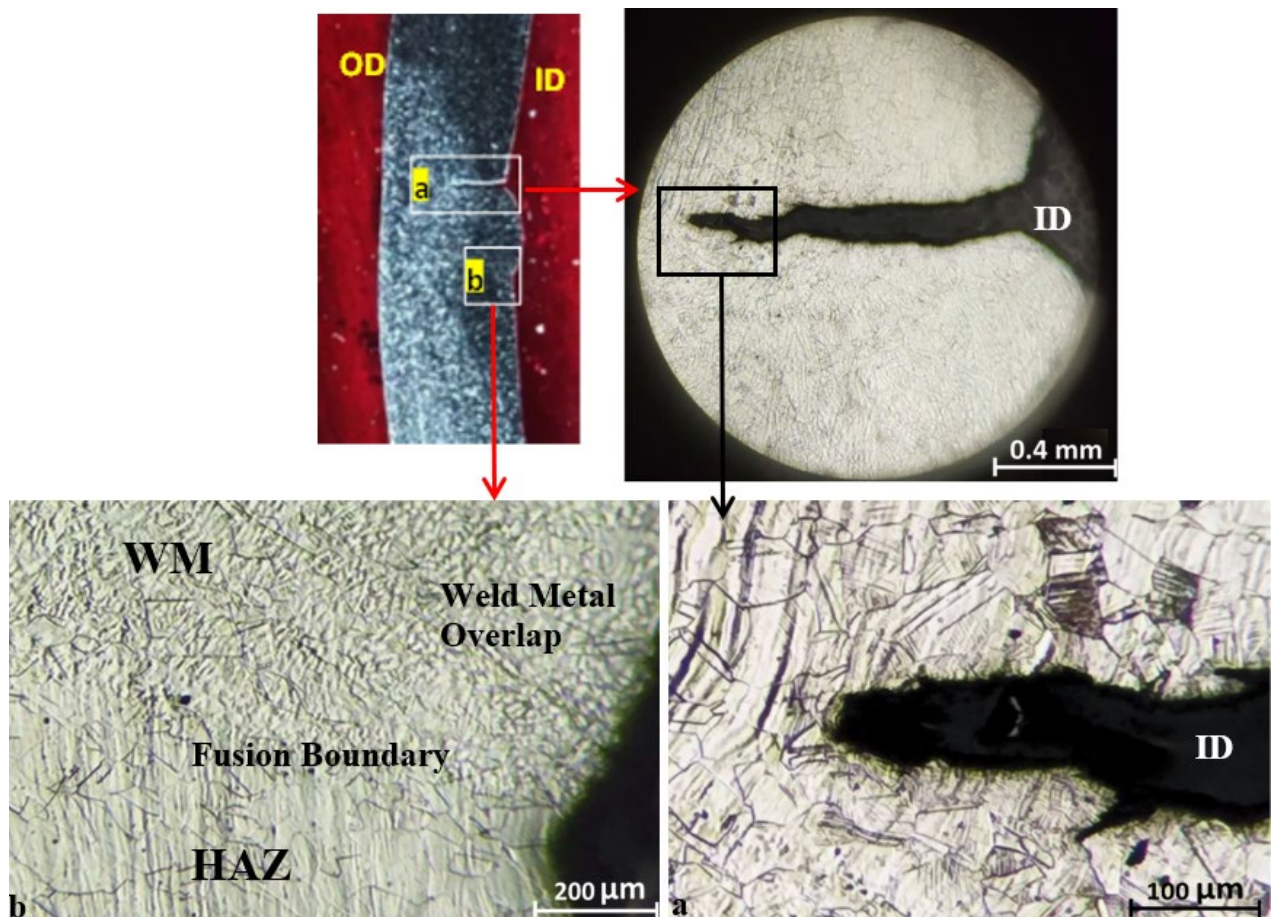


Figure 6. Macrostructure and microstructures of specimen B obtained from the other cracked area at different location from that shown in specimen A (Figure 5) showing formation of one fatigue crack that only penetrated up to the middle of the elbow's wall thickness. The fatigue crack is apparently seen to have initiated from the ID surface at location around the HAZ/fusion boundary of the longitudinal weld of the damaged elbow (etched by aqua-regia)

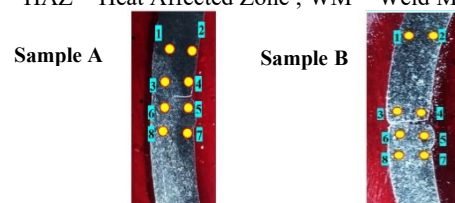
### 3.4 Hardness Test and Analysis

Results of hardness test obtained from specimens A and B of the damaged elbow material are presented in Table 2. It can be seen that the hardness values in the base metal (BM) and HAZ of the damaged elbow material were found ranging from 145.1 to 165.4 HV. These hardness levels are approximately within the range to the hardness levels obtained from the AISI type 316 stainless steel of 227 HV (max). From Table 2, it is also found that in the weld metal (WM) area, the range of hardness levels was relatively higher compared to that obtained from the BM and HAZ, namely 167.8-185.5 HV. These high hardness levels occurred at the WM of the elbow may be resulted from the smaller grain size that formed in the WM microstructure compared to the microstructure obtained from the BM and HAZ. The hardness value on HAZ looks the lowest because it has a coarse grain size so it is prone to cracking.

Table 2. Results of hardness test obtained from specimens A and B of the damaged elbow material using Vickers hardness method (HV) at different test locations

No	Measured Hardness (HV 5)		Test Area
	Sample A	Sample B	
1	156.6	150.4	BM
2	154.6	156.4	
3	145.1	152.9	HAZ
4	152.4	165.4	
5	167.8	177.1	WM
6	185.5	174.5	
7	154.3	148.6	HAZ
8	161.4	167.7	

Note : BM = Base Metal ;  
HAZ = Heat Affected Zone ; WM = Weld Metal



### 3.5 SEM Fractography and EDS Analysis

SEM photographs and the corresponding EDS spectrum of elements obtained from some areas around the fatigue fracture surface of the damaged elbow are presented in Figures 7 and 8. The presence of fatigue striations shown in

Figure 7 indicated that a fatigue crack has been growing in that particular area of the damaged elbow as a result of some cyclic loadings [15]-[16]. As seen in Figure 7, the crack is growing from left to right or from inner side to the outer side of the elbow. Further from Figure 8, it is found that the damage or fracture surface deposit generally contained a number of elements from which the elbow made, such as Fe, Ni, Cr, Mo, Si and Mn. The fracture surface deposit also contained oxygen (O) and carbon (C) as elements

that may be coming from some oxides and/or other surface contamination. It can also be seen from Figure 8 that there were no particular trace elements found in the fracture surface deposit. This indicates that there was likely no any trace elements contributed to the failure of the elbow. This also confirms that the fatigue crack occurred in the elbow is apparently caused by mechanical fatigue and not due to corrosion fatigue.

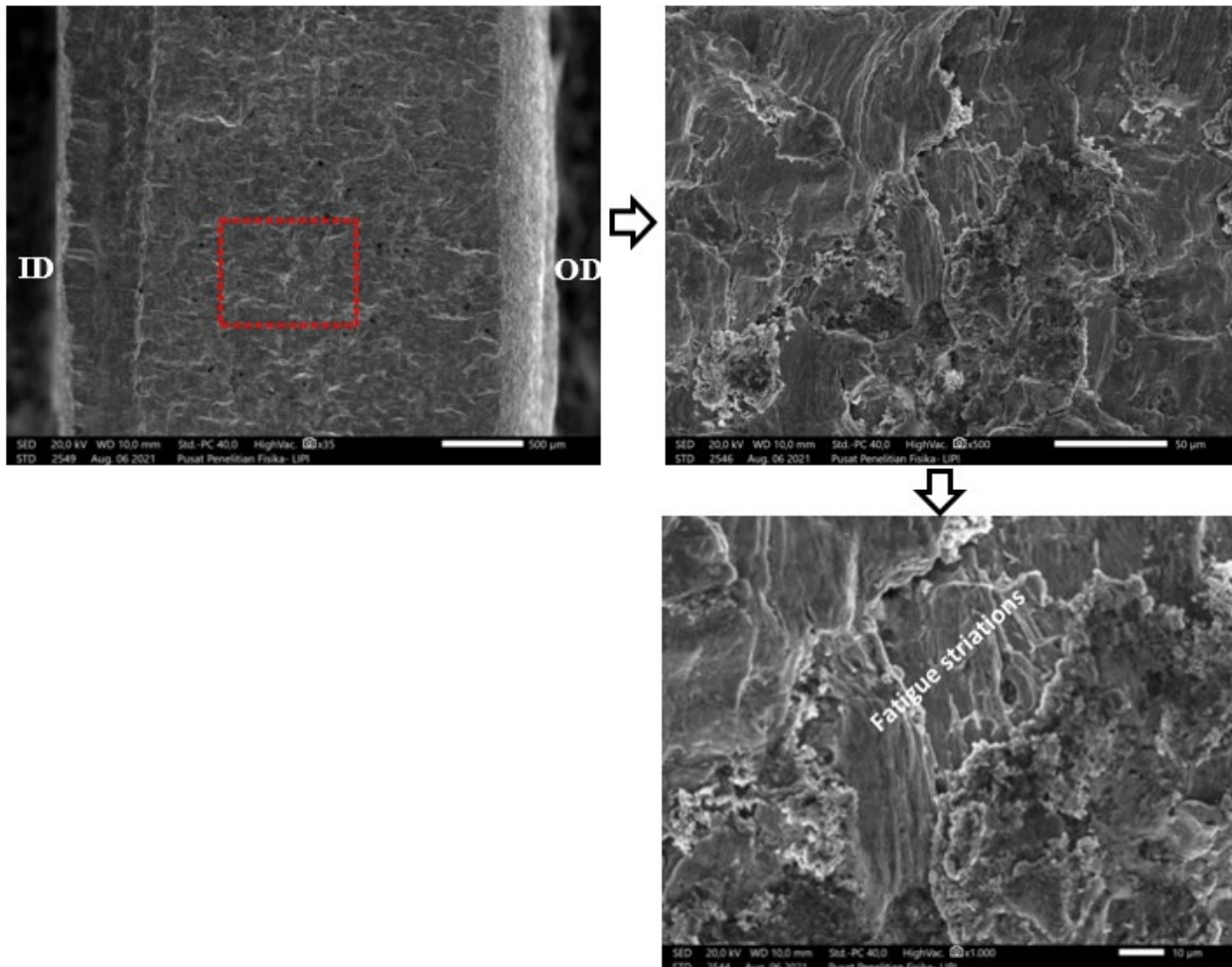


Figure 7. SEM image showing fatigue striations on the fracture surface of the leaking elbow. Formation of fatigue striations are from left to right, or from the ID side to the OD side of the damaged elbow



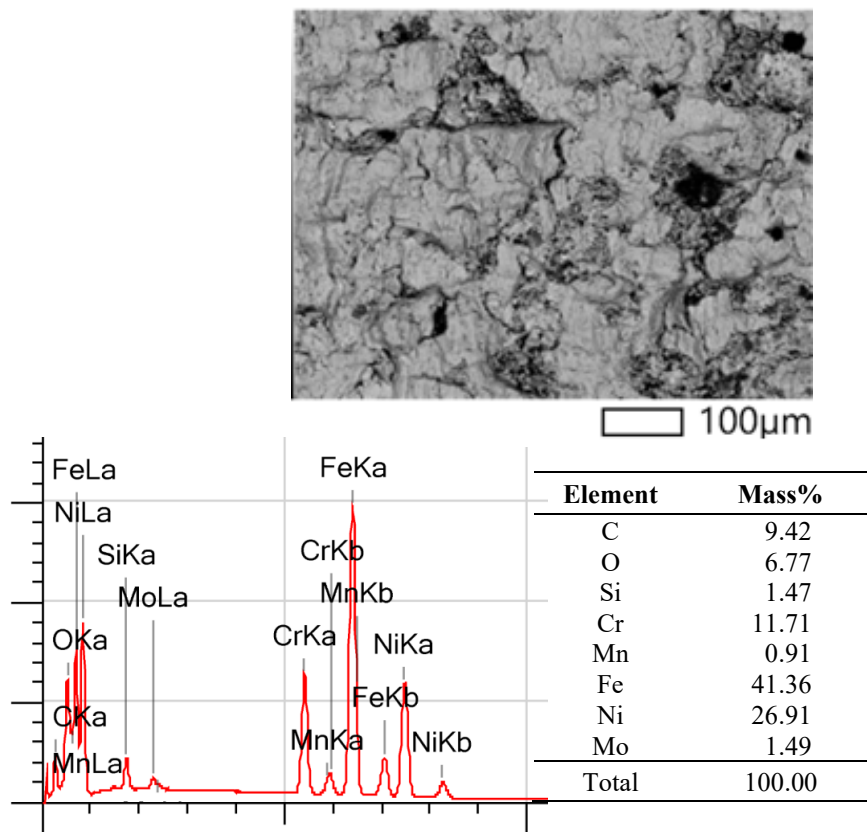


Figure 8. EDS analysis obtained from some fatigue fracture surface of the leaking elbow

#### 4. CONCLUSIONS

According to the crack topography and mode of failure, the elbow had experienced mechanical fatigue due to the cyclic loadings occurred during the frequent draining processes carried out on the fatty acid fluid containing hydrogen gas out of the vessel. Fatigue crack was initiated from the internal wall of the elbow where the weld defect due to imperfect shape in the HAZ/fusion boundary of weld overlap present. The fatigue crack was subsequently propagated in tangential direction toward the outer side of the elbow and eventually forming the final fracture to cause leakage. The material used for the failed elbow was completely met to the material specification of AISI type 316 austenitic stainless steel. This is also supported by the microstructures obtained in which the elbow material showed all austenite phase with several twin boundaries. Furthermore, the hardness values obtained from the elbow material are in the range of hardness value of the material specification of AISI type 316 austenitic stainless steel. The results of SEM photographs obtained show that formation of some fatigue striations was observed in some of the fracture surface of the leaking elbow. This also confirms that the cracks occurred in the

cross section of the elbow are caused by the mechanism of fatigue failure due to cyclic loadings. From the results of the EDS analysis obtained, it shows that almost all of the elements contained in the fracture surface deposit of the leaking elbow come from the elbow material that is made of austenitic stainless steel. It also further confirms that the damage occurred in the elbow is obviously caused by mechanical fatigue and not due to corrosion fatigue.

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#### REFERENCES

- [1] V.S Marpudi and R.S Mehra, "Fatigue failure analysis of an automotive crankshaft and to find its behavior under different operating loads," *Int. J. Eng. Res. Tech*, vol. 3, no. 1, pp. 1338-1342, 2014.
- [2] D. Ariwibowo, S. Putra, S. Darmanto, J. Mrihardjono, and W. Mangestiyono, "Failure analysis of water pump shaft," *J.*

- Voc. Stud. App. Res.*, vol. 1, no. 2, pp. 27-30, 2019. Doi: <http://dx.doi.org/10.14710/jvsar.1.2.2019.27-30>.
- [3] A. Hamid, S. Nugroho, G. D. Haryadi, and Khaeroman, "Failure analysis of shaft circulating water pump (CWP) used in power plant," in *MATEC Web of Conferences 159, 02027*, pp. 1-6, 2018.
- [4] A. Roy, P. Palit, S. Das, and G. Mukhyopadyay, "Investigation of torsional fatigue failure of a centrifugal pump shaft," *Eng. Fail. Anal.*, vol. 112, p. 104511, 2020. Doi: 10.1016/J.ENGFAILANAL.2020.104511.
- [5] N. J. Lourencu, M. L. A Graca, L. A. L. Franco, and O. M. M. Silva, "Fatigue failure of a compressor blade," *J. Eng. Fail. Anal.*, vol. 15, no. 8, pp. 1150-1154, 2008. Doi:10.1016/J.ENGFAILANAL.2007.11.006.
- [6] Y. J. Chen, X. Zhang, F. Wang, and X. Song, "Fatigue failure analysis and life prediction of aero engine compressor components," *J. Mat. Eng. Perform.*, vol. 28, no. 10, pp. 6418-6427, 2019. Doi : 10.1007/s11665-019-04370-y.
- [7] H. Kazempour-Liasi, A. Shafiei, and Z. Lalegani, "Failure analysis of first and second stage gas turbine blades," *J. Fail. Anal. Preven.*, vol. 19, no. 16, pp. 1673-1682, 2019. Doi :10.1007/s11668-019-00764-1.
- [8] P. Puspitasari, A. Andoko, and P. Kurniawan, "Failure analysis of a gas turbine blade : A Review," in *MATEC Web of Conferences 159, 02027*, pp. 1-9, 2021.
- [9] P. Simion, V. Dia, B. Istrate, G. Hrituleac, I. Hrituleac, and C. Munteanu, "Study of fatigue behavior of longitudinal welded pipe," in *IOP Conf. Series : Mat. Sci. and Eng.*, pp. 1034, 2016. Doi : 10.1088/1757-899X/145/2/022032.
- [10] S. M. Beden and M. K. Allawi, "Fatigue life assessment of petroleum pipe elbows," *Int. J. Cur. Eng. Tech.*, vol. 7, no. 1, pp. 92-98, 2017.
- [11] M. F. Harun, R. Mohammad, N. Othman, A. Amrin, S. Chelliapan, and N. Maarop, "Recent advancements in investigations of elbow pipe fatigue under various loading conditions," *Int. J. Mech. Eng. Tech.*, vol. 8, no. 11, pp. 510-527, 2017.
- [12] P. Arora, V. Bhasin, K. K. Vaze, D. M. Pukazhendhi, P. Gandhi, and G. Raghava, "Fatigue crack growth behavior in pipes and elbows of carbon steel and stainless steel materials," *Proc. Eng.*, vol. 55, pp. 703-709, 2013. Doi : <http://dx.doi.org/10.1016/j.proeng.2013.03.318>.
- [13] S. Odahara, Y. Murakami, M. Inoue, and A. Sueoke, "Fatigue failure by flow-induced vibration : Effect of initial defect size on cumulative fatigue damage," *JSME Int.J., Ser. A*, vol. 47, no. 3, pp. 426-437, 2004.
- [14] M. F. I. A. Fuad, N. Lukman, and A. D. Z. A. Nazari, "Flow induced vibration research of oil and gas process piping system," *Int. J. Recent Tech Eng.*, vol. 8, no. 258, pp. 1387-1390, 2016. Doi :10.35940/ijrte.B1072.0882S819.
- [15] A. J. Mc Evily and H. Matsunaga, "On fatigue striations," *Sci. Iran.*, vol. 17, no. 1, pp. 75-82, 2010.
- [16] N. T. Goldsmith, R. J. H. Wanhill, and L. Molent, "Quantitative fractography of fatigue and an illustrative case study," *J. Eng. Fail. Anal.*, vol. 96, pp. 426-435, 2019.
- [17] D. N. Adnyana, "Corrosion fatigue of a low-pressure steam turbine blade," in *J. Fail. Anal. and Preven.*, vol. 18, no. 1, pp. 162-173, 2018.