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FAILURE OF A HEAT EXCHANGER RETURN BEND DUE TO LONG-TERM LOCALIZED OVERHEATING

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Intisari

Tulisan ini menyajikan penelitian yang dilakukan pada sebuah belokan pipa U (*return bend*) pada sebuah alat penukar kalor yang mengalami kerusakan (pecah) setelah beroperasi hanya dalam waktu 2,5 tahun. Alat penukar kalor tersebut digunakan untuk memindahkan panas dari gas panas hasil pembakaran pada sisi bejana/tabung ke dalam bahan baku minyak (*feedstock oil*) pada sisi pipa. Material belokan pipa U tersebut dibuat dari baja karbon dengan standar ASTM A-234 Gr.WPB, memiliki diameter 2 inch dan tebal SCH 80. Penelitian berupa observasi dan pengujian metalurgi dilaksanakan dengan menyiapkan sejumlah sampel material dari belokan pipa U, baik yang sudah pecah maupun yang tidak pecah. Pengujian yang dilakukan meliputi uji visual dan makro, analisa kimia, uji metalografi, uji kekerasan dengan metoda Vickers dan SEM (*scanning electron microscopy*) - EDS (*energy dispersive spectroscopy*). Hasil pengujian metalurgi menunjukkan bahwa pipa belokan U yang pecah mengalami kerusakan akibat beban berlebih yang dipengaruhi oleh *local hot spot* atau panas berlebih secara lokal dalam jangka panjang (*long-term localized overheating*). Akibatnya, tegangan yang bekerja pada dinding belokan pipa U mengalami peningkatan yang sangat signifikan sehingga pada akhirnya tekanan operasi yang terjadi pada bahan baku minyak di dalam pipa dapat merobek atau memecahkan bagian dinding belokan pipa U tersebut.

***Kata Kunci** : Baja karbon standar ASTM A-234 Gr.WPB, belokan pipa U, alat penukar kalor*

Abstract

This paper presents a metallurgical assessment performed on a return bend of a heat exchanger that had failed due to bursting after it had been only about 2.5 years in service. The heat exchanger was used to transfer heat from hot combustion gas on the shell side to the feedstock oil on the tube side. The return bend material was made of standard wrought carbon steel of ASTM A-234 Gr.WPB, having a diameter of 2 inches and wall thickness of SCH 80. The metallurgical assessment was conducted by preparing several specimens from the as-received burst and unburst return bends. Various laboratory examinations performed including visual and macroscopic examination, chemical analysis, metallographic examination, hardness testing by Vickers method, and SEM (scanning electron microscopy) equipped with EDS (energy-dispersive spectroscopy) analysis. Results of the metallurgical assessment obtained showed that the burst return bend had been experiencing fracture overload due to a local hot spot or long-term localized overheating occurred on the outer bend external surface. Consequently, the hoop stress at the outer bend section had been increasing significantly and eventually, the working pressure of the feedstock oil on the tube side could burst the return bend wall thereon.

***Keywords**: Carbon steel of ASTM A-234 Gr. WPB, return bend, heat exchanger*

1. INTRODUCTION

A shell and tube heat exchanger is the most common type of heat exchanger in oil and petrochemical processes and is suitable for high-pressure applications. This type of heat exchanger consists of a shell (a large pressure vessel) with a bundle of tubes inside it. Depending on the design, at the end section of the shell, the tubes are often connected one to the other using U tube or return bend. One fluid runs through the tubes, and another fluid flows through the shell to transfer heat between the two fluids. From the techno-economic consideration and based on the operating condition and type of fluid applied, most of the material used for tube and return bend made of low carbon steel or low alloy steel.

Types of failures and damage mechanisms of the heat exchangers are well presented in several articles in the literature [1]-[8]. Failures in heat exchanger are commonly associated with methods of manufacturing of tubes/return bends, handling methods during fabrication, testing methods in the shop and in the field, and the total environment to which the unit is exposed after fabrication. In some cases, failures in the heat exchanger may also be influenced by design fault or by improper material selection [5]-[6]. In addition, type of fluids or liquids flowing in the heat exchanger together with the operating condition may also be an important factor in affecting to the heat exchanger failures [7]. Moreover, another performance problem in heat exchanger operation includes excessive tube fouling [9]-[10]. Major detrimental effects of fouling include loss of heat transfer as indicated by charge outlet temperature decrease and pressure drop increase. Other detrimental effects of fouling may also include blocked process tubes/return bends, under-deposit corrosion and pollution. Where the heat flux is high, fouling can lead to local hot spots resulting ultimately in mechanical failure of the heat transfer surface. Such effects lead in most cases to production losses and increased maintenance costs.

In the feedstock oil that utilized in this heat exchanger, similar to the most of crude oils, two types of fouling predominate [11]. These are in organic fouling in which deposits mainly consist of FeS and salts, and organic fouling due to asphaltenes which ultimately result in coke deposits. These two types of fouling may occur together, or separately, depending on circumstances. According to the previous research work [11], the inorganic fouling likely occurred at low temperature, while as the temperature rises along the tube at about 350 °C, fouling appears more likely to be caused by organics. Coke formation starts near the wall and then propagates towards the center of the heat exchanger tube or return bend as well. The coke near the wall is generally found to be hard and difficult to be removed [12]. As the fouling deposit layer builds up, the thermal efficiency drops and pressure drop increases significantly leading to some formation of localized overheating or hot spot on the tube or return bend external surfaces. If the temperature rise due to localized overheating is significantly high, the tube or return bend material will be subjected to some metallurgical degradation, leading to lower its tensile strength. In addition, localized overheating could also increase the corrosion rate on the tube or return bend external surface, resulting in wall thinning or metal loss thereon. Consequently, the level of hoop stress occurring on the tube or return bend section could increase significantly and therefore the tube burst cannot be avoided.

The purpose of this failure analysis was to verify the material properties and to determine whether the material used for the return bend met the specification or suitable for its operating condition. Furthermore, this failure analysis was also aimed to establish the type, cause, and mode of failure of the burst return bend, and based on the determination, and some corrective or remedial action may be initiated that will prevent a similar failure in future.

2. MATERIALS AND METHOD

In this failure analysis, two return bends of the damaged heat exchanger were used. One of this return bends had experienced bursting after the heat exchanger had been only about 2.5 years in service. The as-received two returns bends for analysis are seen in Figure 1. Visually, bursting shown in Figure 1 occurred at one of the outer bend external surfaces. The return bends shown in Figure 1 are typical elbow 90° LR, having a diameter of 2 inches and the wall thickness of SCH 80. The return bend material was made of ASTM A-234 Gr. WPB, a standard specification for the piping fitting of wrought carbon steel for moderate and high-temperature service. The heat exchanger was used to transfer heat from hot combustion gas on the shell side to the feedstock oil on the tube side. The tube material of the heat exchanger was made of ASTM A-106 Gr. B, a standard specification for seamless carbon steel pipe for high-temperature service. Similar to the return bend, the tube had a dimension of 2 inches in diameter and wall thickness of SCH 80. The design operating parameters of the heat exchanger were as follows: design pressure and temperature of hot combustion gas on the shell side: 0.5 kg/cm2g and 650 °C, design pressure and temperature of the feedstock oil on the tube side: 45.0 kg/cm2g and 220 °C, and the feedstock oil velocity on the tube side: 10 m3/hr.

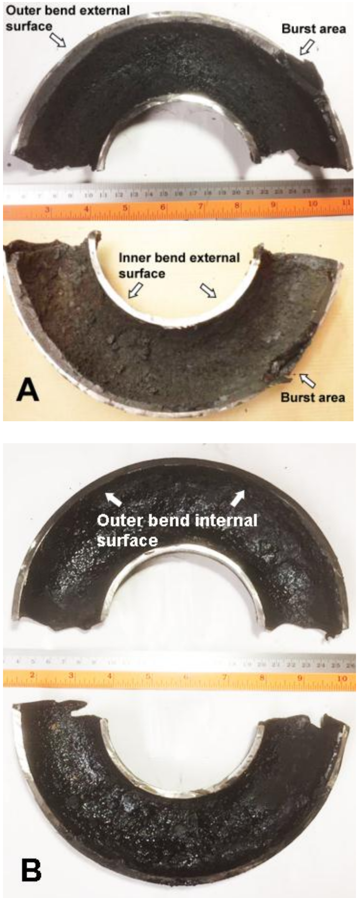


Figure 1. The as received two return bends A and B for analysis (A: burst return bend, and B: unburst return bend). Both return bends were cut away into two half sections

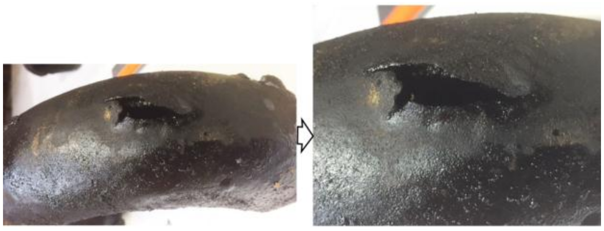


Figure 2. Close up view of the burst return bend, showing some excessive thinning or metal loss occurred around its burst and bulging area on the outer bend external surface

In this failure analysis, the burst return bend (A) and the unburst return bend (B) shown in Figure 1 cut away from the heat exchanger shown in Figure 2. Both of the as-received return bends were then cut into several specimens for laboratory examination. Macroscopic examination on the burst return bend was performed using a stereomicroscope. Chemical analysis of the prepared sample was carried out using optical spark emission spectrometer. The purpose of the chemical analysis was to determine whether the material used for the burst return bend met the specification. Besides, 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 5% Nital solution [13]. A hardness survey was also carried out on the same samples for metallographic examination using the Vickers hardness method at a load of 5 kg (HV 5).

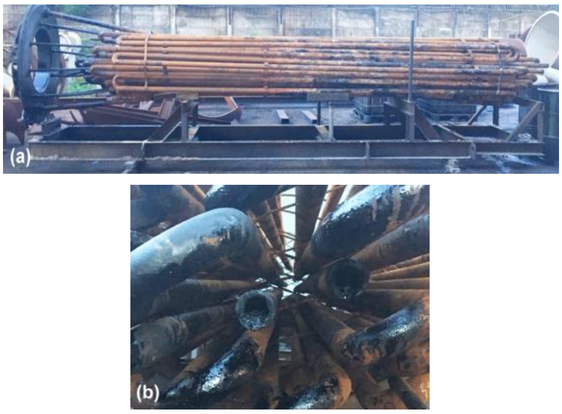


Figure 3. (a) Disassembled tubes bundle from the heat exchanger shell, (b) End section of the tubes bundle showing the location of the burst return bend that was cut away

Moreover, an examination of some internal and external deposits of the burst return bend was also performed using SEM (scanning electron microcopy) to determine the deposit topography. This SEM was also equipped with EDS (energy-dispersive spectroscopy) analysis to detect the presence of any element(s) that formed the deposit layer, or any corrosion by-product.

3. Results And Discussion

3.1. Visual and Macroscopic Examination

Close-up view of some damaged area of the burst return bend shown in Figure 1 is presented in Figure 3, showing the formation of some excessive thinning or metal loss occurred around the bulging and burst area on the outer bend external surface. It is seen that most of the deposits formed on the outer bend external surface were peeled off from the surface. Besides, it can also be seen from Figure 3 that the burst formed on the outer bend external surface where most of the thinning occurred. Similar surface thinning was also observed on the unburst return bend, particularly on both of its outer bend external surfaces (see Figure 1(a)). Further information obtained from Figure 3 is that the surface thinning or metal loss occurred on the outer bend external surface was most likely related with the formation of some thick fouling deposit layer that formed on the outer bend internal wall (see also Figure 4(a)). In Figure 4(b), it shows some deposit that was obtained from the outer bend internal wall shown in Figure 4(a).

Like those above, the formation of a thick deposit on the outer bend internal wall of the burst return bend caused by laminar flow and abrupt pressure changes that were present on the outer bend internal wall [9]-[10]. This may have caused some inadequate cooling effect of the feedstock oil to the outer bend wall and resulted in local hot spot or long-term localized overheating on the outer bend external surface. Consequently, this local hot spot may have increased the rate of corrosion significantly on the outer bend external surface, and eventually it could also increase the thinning or metal loss thereon.

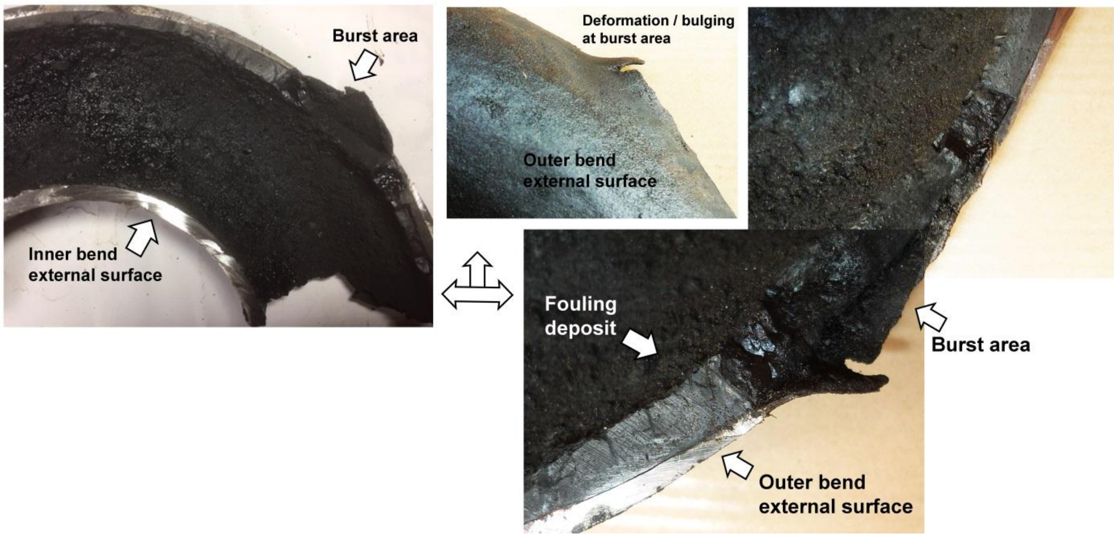


Figure 4. Close up view of the sectioned burst return bend around its outer bend section where the failure occurred. Note the build-up of massive fouling deposit on the outer bend internal wall where most of the excessive thinning happened on the outer bend external surface

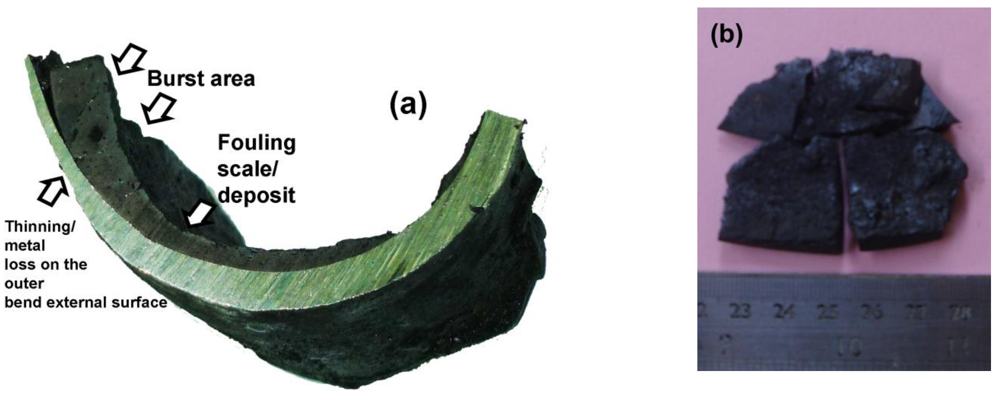


Figure 5. (a) Appearance of some internal deposits that formed on the outer bend inner wall of the burst return bend. (b) Note some collected fouling deposit that obtained from the outer bend internal wall

3.2 Chemical Analysis

Result of the chemical analysis obtained from the material used for the burst return bend in comparison with the standard equipment is presented in Table 1. It can be seen that the chemical composition of the burst return bend material is a type of low carbon steel and approximately close to the material specification of ASTM A-234 Gr. WPB, a standard specification for the piping fitting of wrought carbon steel for moderate and high-temperature service [14].

Table 1. Result of chemical analysis obtained from the burst return bend material in comparison with the standard material

Element	Composition, wt %	
	Burst Return Bend	Standard Material ASTM A-234 Gr. WPB
Fe	98.8	Balance
C	0.193	0.3% (max)
Mn	0.413	0.29 - 1.06%
Si	0.263	0.10% (min)
Cr	0.0203	0.40% (max)
Ni	0.0419	0.40% (max)
P	0.0128	0.05% (max)
S	< 0.0030	0.058% (max)
Mo	< 0.0040	0.15% (max)
Cu	0.119	0.40% (max)
Nb	0.0055	0.02% (min)
V	0.0059	0.08% (min)

3.3 Metallographic Examination and Analysis

For metallographic examination, two specimens were made from the burst return bend, one cut and prepared in a transverse direction, and the other was cut in a longitudinal direction (see Figures 5 and 6). In addition, another specimen in transverse direction prepared from the unburst return bend. This specimen was cut away from the outer bend section where most of the thinning occurred on its external surface.

Microstructures obtained from the outer bend transverse section around the burst area presented in Figure 5. The microstructures received show matrix ferrite phase (light color) and a small of second pearlite phase (dark color), typical of low carbon steel. The microstructures obtained also supported to or following the result of chemical analysis shown in Table 1. In addition, the microstructures obtained also show some possible formation of carbide spheroidization or graphitization, although it may be still in its early stage. Furthermore, it also noticed that from Figure 5 a few number of isolated creep cavities may have formed. Moreover, from Figure 5, it can also be seen that general uniform corrosion along with some localized corrosion such as under-deposit corrosion or stress corrosion may have also formed on some internal wall of the burst return bend.

Microstructures obtained from the outer bend longitudinal section of the burst return bend presented in Figure 6. The microstructures obtained are very much similar to those obtained from the outer bend transverse sectional area of the burst return bend in which some carbide spheroidization and isolated creep cavitation may have started to form in the microstructures. Also, there were also likely several small graphite nodules formed. Furthermore, from Figure 6, it can also be seen that both of the outer bend surfaces, either the internal surface or the external surface had damaged by corrosion. The external surface may have been experiencing some pitting and surface corrosion, while the inner surface where some thick deposit formed, it may have been experiencing some localized corrosion such as under-deposit corrosion and/or stress corrosion. It appeared that this localized corrosion might have produced some strong adherent deposit layers on the outer bend internal surface. However, the formation of this localized corrosion may have also contributed to the acceleration of the return bend failure.

Formations of carbide spheroidization and graphitization observed on the microstructures obtained from the outer bend transverse section of the unburst return bend (see Figure 7). According to Figure 8, this carbide spheroidization is a change in the microstructure of certain carbon steels and low-alloy steels after long-term operation in the 440 ºC to 760 ºC, and may cause a loss in strength and/or creep resistance [15]. Spheroidization can occur in a few hours at 552 ºC, but may take several years at 454 ºC [16]. At elevated temperatures, the carbide phases or pearlitic microstructures in these steels are unstable and may agglomerate from their normal plate-like form to a spheroidal form. As seen in Figure 8, in addition to spheroidization, other decomposition mechanisms, which are known as graphitization may also occur [15]-[16]. The temperature has an important effect on the rate of graphitization.

Below 427 ºC, the rate is extremely low. The rate increases with increasing temperature. Graphitization may cause a loss in strength, elasticity, or creep resistance.

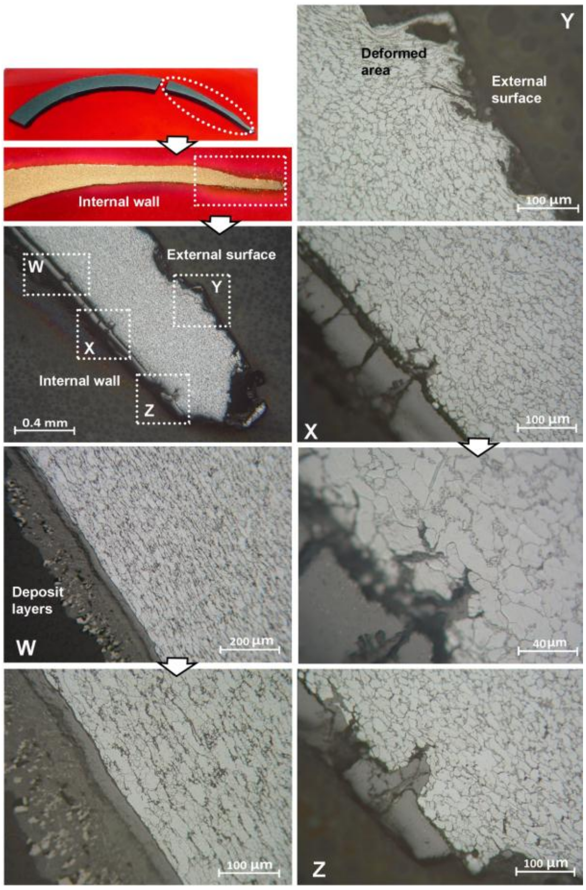


Figure 6. Microstructures obtained from the outer bend transverse section of the burst return bend (around the burst area) at different locations indicated by the square grids. Etched with 5% Nital solution

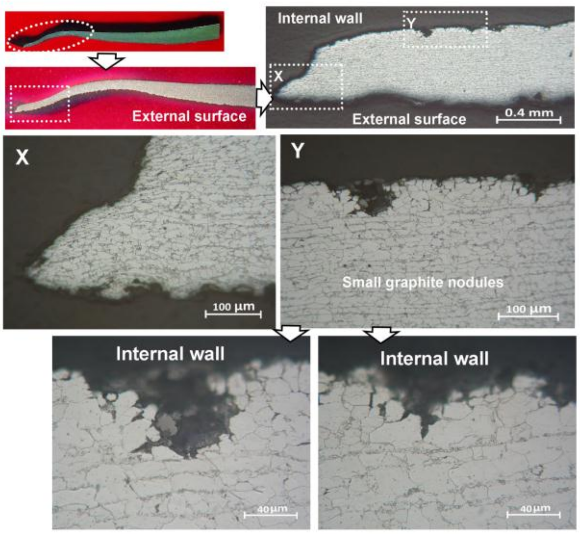


Figure 7. Microstructures obtained from the outer bend longitudinal section of the burst return bend (around the burst area) at different locations indicated by the square grids. Etched with 5% Nital solution

Based on the mentioned decomposition mechanisms and formation of some creep cavitation in the microstructures obtained, it is likely that the outer bend metal temperature may have reached approximately in the range of 375 to 450 °C for quite a long time or several years. This temperature range is approximately well above the design metal temperature of the return bend material, which is made of low carbon steel (ASTM A-234 Gr. WPB). Since the design operating temperature of the feedstock oil on the tube side was only 220 °C, and the design temperature of the hot combustion gas on the shell side was 650 °C, this indicated that the heat flux occurred on the outer bend section is higher than the ability of feedstock oil to absorb and accommodate the heat flux. This condition indicated that the outer bend section of the return bends (where a thick internal deposit formed) might have been subjected to some local hot spot or a long-term localized overheating.

3.4 Hardness Test and Analysis

Table 2 shows the results of the hardness test obtained from the burst and unburst return bend material. It saw that the hardness values obtained are in the range of 130 HV to 148 HV, typical hardness values for low carbon steels in annealed or normalized condition [17]. These hardness test results also further supported that the return bend material was made of low carbon steel with the specification of ASTM A-234 Gr. WPB [18]. The design operating temperature of hot combustion gas on the shell side of 650 °C was too high for the return bend or tubing material which only made of low carbon steel. This condition based on the fact that the threshold temperature of carbon steels for creep and other metallurgical degradation, such as a spheroidization or a graphitization is approximately 370 °C [19].

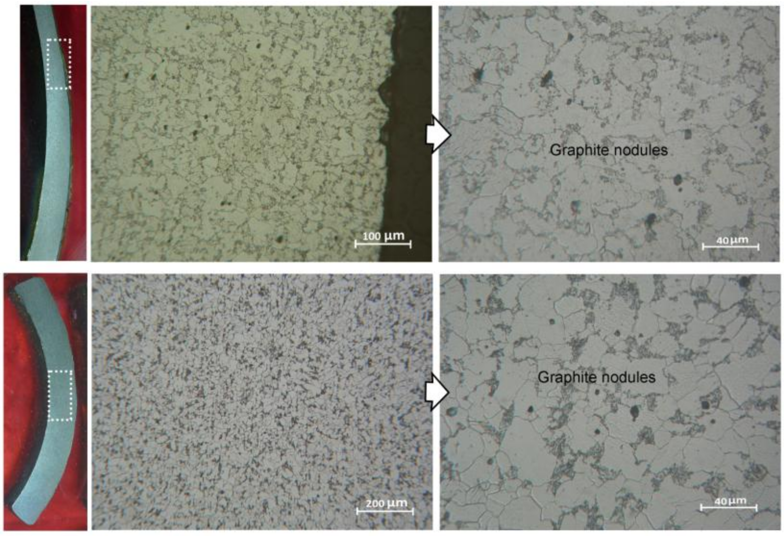
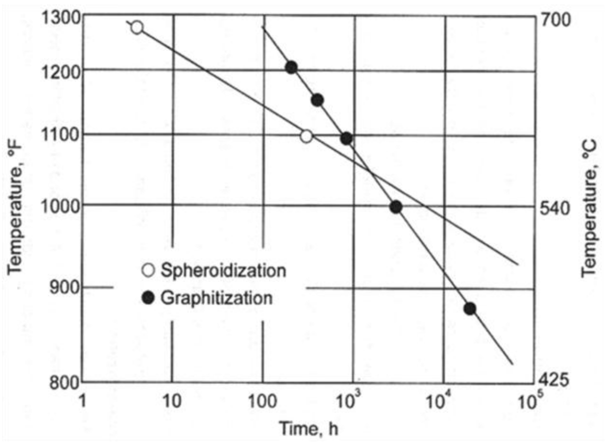


Figure 8. Microstructures obtained from the outer bend transverse section of the unburst return bend at different locations indicated by the square grids. Etched with 5% Nital solution



Gambar 9. Grafik kekerasan paduan Co-26Cr-6Mo dan paduan Co-26Cr-6Mo-0,18N

From Table 2, it saw that hardness values of the outer bend external surface where most of the thinning process occurred are slightly lower than the average hardness values of the return bend material. This lower hardness was most likely caused by the high-temperature exposure (local hot spot) occurred on the particular area of the return bend. In addition, from Table 2, it can also be seen that hardness values of the outer bend material in the burst area are generally higher than the average hardness values of the return bend material. This higher hardness was caused by strain hardening effect due to some deformation occurred on the return bend material in the event of bursting [14].

Table 2. Results of hardness test obtained from different test locations of the burst return bend material (A) and the unburst return bend material (B) using Vickers hardness method (HV)

No	Hardness Value (HV 5)				
	Samples from Burst Return Bend (A)				
	Transverse Cross Section (A1)	Cross Section Around the Burst Area (A2)		Longitudinal Section (A3)	Longitudinal Section Around the Burst Area (A4)
1	**132.0**	133.0	Near to burst area	148.0	169.0
2	**131.0**	133.0		147.0	152.0
3	**130.0**	135.0		134.0	130.0
4	**135.0**	Far from burst area	135.0	136.0	132.0
5	**132.0**		130.0	143.0	132.0
6	**133.0**	At outer bend external surface	144.0	141.8	-
7	**123.8**			-	-
8	**128.0**			-	-
Average	-	133.7	-	141.6	-

Table 3. Results of hardness test obtained from different test locations of the burst return bend material (A) and the unburst return bend material (B) using Vickers hardness method (HV), continued

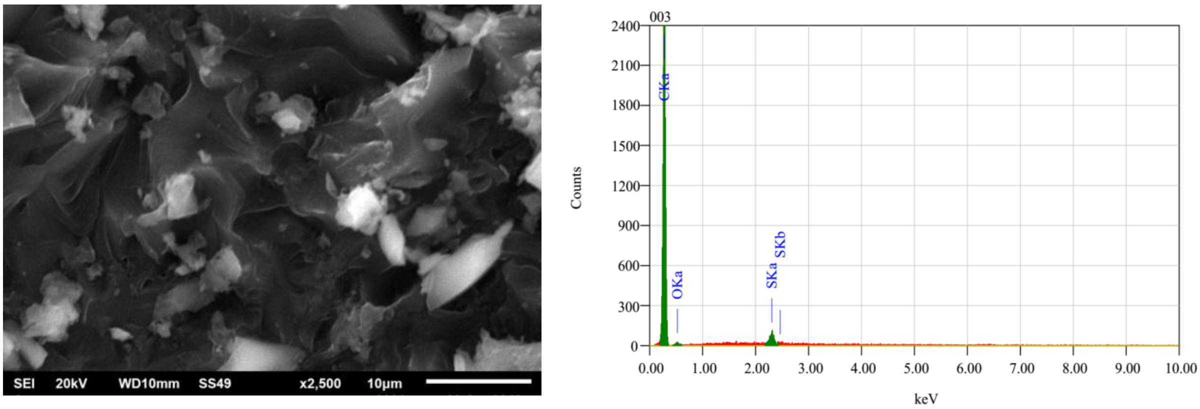
No	Hardness Value (HV 5)	
	Samples from Unburst Return Bend (B)	
	Longitudinal	Transverse
1	134.0	128.0
2	143.0	138.2
3	135.0	137.0
Average	137.3	134.4

3.5 SEM and EDS Analysis

SEM (scanning electron microscopy) micrographs and the corresponding EDS (energy dispersive spectroscopy) spectrum of elements from some external and internal deposits obtained around the burst area presented in Figures 9 and 10. From the results obtained, it indicated that most of the deposit formed on the outer bend internal wall surface of return bend was containing with significant carbon elements from which the coke deposit may have formed. In addition, some other aspects in relatively lower percentage such as O (oxygen), S (sulfur), and probably some Fe (iron) also obtained in the internal fouling deposit. Most of these elements may be coming from the flowing feedstock oil on the tube/return bend side. It considered that iron sulfide (FeS) and coke deposition are likely among the most critical causes of formation of such fouling deposit on the bend internal wall surfaces [9]-[10]. Similarly, the deposit that may have formed on the outer bend external surface also containing with significant carbon (C) elements, oxygen (O), iron (Fe) and sulfur (S), whereas the other features in small percentage may have also formed including aluminum (Al) and silicon (Si). Some of these elements such as O, C and S may have been contributing to the oxidation, pitting or corrosion that could cause thinning or metal loss occurred on some of the return bend external surface. Most of the elements are containing in the external deposit may be coming from the flowing hot combustion gas on the shell side.

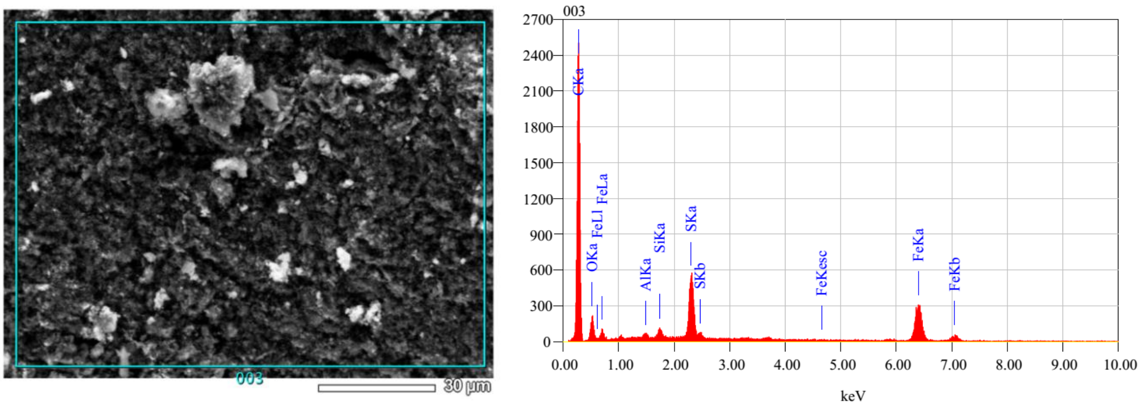
Based on the test results and analysis below, it considered that two types of fouling might have predominated in this heat exchanger, namely inorganic fouling in which deposits mainly consist of FeS and salts, and organic fouling due to asphaltenes which ultimately result in coke deposit [10]. These two types of fouling may have occurred together or separately. The fouling deposit on the internal wall of the return bend/ tube may affect the operation of heat exchanger due to pressure drop increase, heat transfer reduction, hot spot, and corrosion.

The outer bend section of return bend that experienced high-temperature and reached well above its design metal temperature (called as a local hot spot or localized overheating) may also have caused the outer bend external surface subjected to relatively higher rates of oxidation or hot gas side corrosion. The high oxygen (O) content found in the SEM/EDS results may be related to the formation of oxide scales on the outer bend external surfaces, while sulfur (S) content found on the external deposit may have come from the occurrence of corrosion due to sulfidation. The temperature occurred on the outer bend external surfaces was favorable to such corrosion/sulfidation to proceed [20]. This oxidation or corrosion would increase the metal loss of the outer bend external surfaces. Consequently, the thinning occurred could increase the hoop stress, leading to increased damage accumulation rates and hence could bring the outer bend section to become prone or vulnerable to fracture overload. As some gross plasticity may have formed on the bulging and burst area (see Figures 1, 3, 5 and 6), this also indicated that the burst return bend had experienced typical of fracture overload.



Element	C	O	S
Mass Percentage %	95.54	3.01	1.44

Figure 10. SEM and EDS analysis obtained from some inner deposit formed around the outer bend internal wall of the burst return bend



Element	C	O	Al	Si	S	Fe
Mass Percentage %	73.0	12.22	0.26	0.49	3.96	10.07

Figure 11. SEM and EDS analysis obtained from some external deposit formed around the outer bend external surface of the burst return bend

In summary, factors affecting the failure of return bend of the heat exchanger under study and the corresponding damage sequence be described and presented in the flow diagram shown in Figure 12.

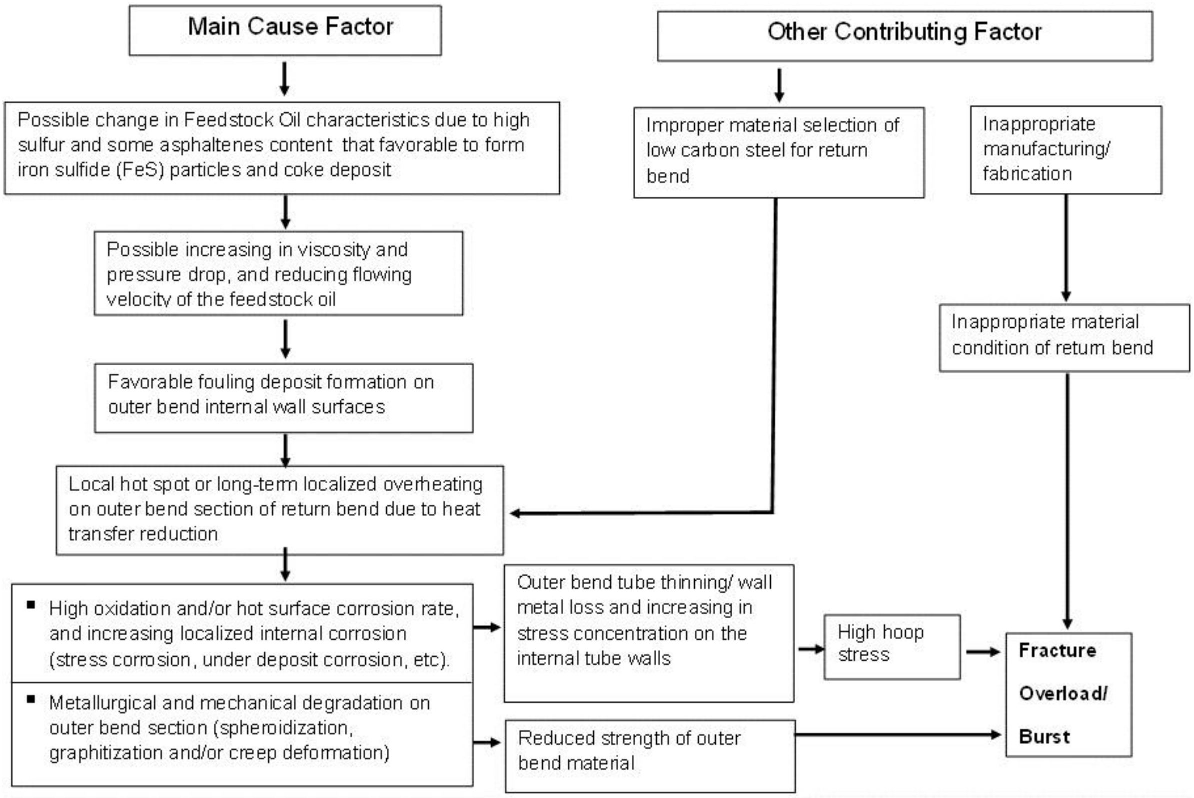


Figure 12. Factors affecting the failure of burst return bend and the corresponding damage sequence

4. CONCLUSION

According to the burst topography and mode of failure, the return bend of the heat exchanger under study had experienced fracture overload due to a local hot spot or long-term localized overheating occurred on the outer bend external surface. The long-term localized overheating occurred may have resulted from the internal deposit build up, causing an inadequate cooling effect of the feedstock oil to the outer bend external surface of return bend. Most likely, the type of fouling deposit that built upon the outer bend internal surface was coke deposit.

Due to this long-term localized overheating, the outer bend external surface was subjected to high corrosion rate caused by corrosive agents containing in the hot combustion gas on the shell side (under the design operating temperature of 650 °C), leading to excessive thinning or metal loss took place at location around the outer bend external surfaces. Beside, some localized corrosion occurred on the outer bend internal wall such as under-deposit corrosion or stress corrosion may have also contributed to the acceleration of the return bend failure.

The material used for return bends of the heat exchanger under study was approximately met to the material specification of ASTM A-234 Gr. WPB. However, application of this material was most likely not suitable or appropriate for return bends or tubing of the heat exchanger based on the process fluid and operating parameter applied. The design operating temperature of hot combustion gas on the shell side of 650 ºC was too high for the return bend or tubing material which only made of low carbon steel. This condition based on the fact that the threshold temperature of carbon steels for creep and other metallurgical degradation such as a spheroidization and/or a graphitization is approximately 370 ºC.

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