STRESS-CORROSION CRACKING IN A NICKEL-BASE ALLOY PRE-HEATER EXPANSION BELLOWS

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Intisari

KOROSI RETAK TEGANG PADA PADUAN BERBASIS NIKEL BELLOWS EKSPANSI ALAT PEMANAS MULA. *Makalah ini menyajikan hasil analisa kerusakan pada sebuah bellows ekspansi yang pecah yang terpasang pada sebuah alat pemanas mula (alat penukar kalor). Bellows tersebut merupakan jenis bellows dengan lapisan pelat bergelombang tunggal, terdiri dari lima lilitan konvolut dan terbuat dari paduan nikel dengan spesifikasi Inconel 625. Fluida yang dialirkan di dalam alat pemanas mula pada sisi tabung atau bejana adalah uap pada suhu operasi 265 °C dan tekanan 51,0 kg/cm*^{2}*g. Bellows tersebut dilaporkan pecah pada suatu kecelakaan/insiden yang terjadi setelah alat pemanas mula tersebut dioperasikan selama lebih dari lima tahun. Sejumlah benda uji disiapkan dari bellows yang pecah tersebut untuk pengujian laboratorium seperti uji makroskopik, analisa komposisi kimia, uji metalografi, uji kekerasan, dan pengujian SEM (scanning electron microscopy) yang dilengkapi dengan analisa EDS (energy dispersive spectroscopy). Hasil analisa kerusakan yang diperoleh menunjukkan bahwa bellows ekspansi yang pecah tersebut utamanya telah mengalami retak korosi tegangan (RKT) yang disebabkan oleh efek simultan antara tegangan tarik dan unsure korosif yaitu sodium (Na) yang merupakan agen korosi kostik utama. RKT yang terjadi umumnya terkonsentrasi pada sisi atas konvolut bellows, diawali dari dinding bagian dalam lengkungan konvolut bagian luar, dan selanjutnya merambat ke arah luar dengan pola retak antar butir yang bercabang secara luas melalui batas butir austenit material bellows. Tingkat dan kondisi retak yang terjadi sangat dipengaruhi oleh tingkat tegangan lentur tarik yang terbentuk pada lengkungan konvolut, dan karenanya kebanyakan retak utama diketemukan terjadi pada bagian paling atas lengkungan konvolut, dimana daerah tersebut mengalami tegangan tarik maksimum atau tertinggi. Pada daerah dengan tegangan tarik yang lebih rendah atau tanpa tegangan tarik, pola kerusakan yang terjadi kemudian berubah menjadi pola korosi antar butiran.*

Kata kunci : Bellows ekspansi, Alat pemanas mula, Retak korosi tegangan (RKT), Inconel 625

Abstract

STRESS-CORROSION CRACKING IN A NICKEL-BASE ALLOY PRE-HEATER EXPANSION BELLOWS. This paper presents the results obtained from the failure analysis performed on a ruptured expansion bellows of a pre-heater. This bellows is a typical of single ply corrugated bellows consisting of five bellows convolutions and was made of Inconel 625, a standard specification for Ni-base alloy. The fluid circulated within the pre-heater on shell side was steam at the operating temperature and pressure of 265°C and 51.0 kg/cm^{2}g, respectively. The bellows was reportedly ruptured during an accident occurred after the pre-heater had been in service for more than five years. A number of specimens were prepared from the ruptured bellows for laboratory examinations including macroscopic examination, chemical analysis, metallographic examination, hardness test, and SEM (scanning electron microscopy) examination equipped with EDS (energy dispersive spectroscopy) analysis. Results of the failure analysis obtained showed that the ruptured expansion bellows had experienced predominantly to stress corrosion cracking (SCC) caused by the simultaneous presence of tensile stress and a corrosive agent in which sodium (Na) was found being the major caustic corroding agent. Most of the SCC occurred were concentrated on the upper or top side of the bellows convolutions and initiated from the inner wall of the outer bend convolutions and subsequently propagated outward in intergranular manner with extensive branching through the austenitic grain boundaries of the bellows material. The severity of cracking was very much affected by the level of tensile bending stresses present on the bend convolutions, and therefore most of the main crack rupture was found to take place at the peak bend convolutions where the tensile stress

was maximum or highest. In some area having less or no tensile stress, the damage pattern was predominantly altered into the intergranular corrosion.

Keywords: Expansion bellows, Pre-heater, Stress-corrosion cracking (SCC), Inconel 625

INTRODUCTION

An expansion joint bellows of a pre-heater having similar construction with that shown in Fig.1 was found ruptured after the pre-heater had been in service for more than five years. The pre-heater is a typical shell and tube heat-exchanger with a cross/counter flow arrangement and was used to transfer heat from steam on the shell side to slurry in the tube side. The operating parameters of the pre-heater were as follows: operating pressure in the shell side: 51.0kg/cm^{2}g while in the tube side: 124.0kg/cm^{2}g, operating temperature in the shell side: 265 °C, and the operating temperature in the tube side: 246.4 °C (inlet) and 255.7 °C (outlet). The pre-heater tube material is made of duplex stainless steel type 2205 (UNS S31803) [1]. The ruptured bellows which is shown in Fig.2 is a typical of single ply corrugated bellows consisting of five bellows convolutions and equipped with four reinforced rings, two end reinforced rings, two reinforced ribs and an external cover. The bellows is designed to be subjected only to axial deflection and could be either extension or compression depending on the differential expansion of pre-heater shell and tubes. The bellows material is made of Inconel 625, a standard specification for nickel-base alloy. In addition, the ruptured bellows is typical of thin wall multi-convolution bellows, having only 2.20-2.50 mm in thickness.

Figure1. Photograph of a pre-heater equipped with an expansion bellows

Figure 2. The ruptured expansion bellows showing four of its five bellows convolutions that were severely damaged due to cracking. Most of the cracks rupture occurred on the upper side or top side of the bellows convolutions

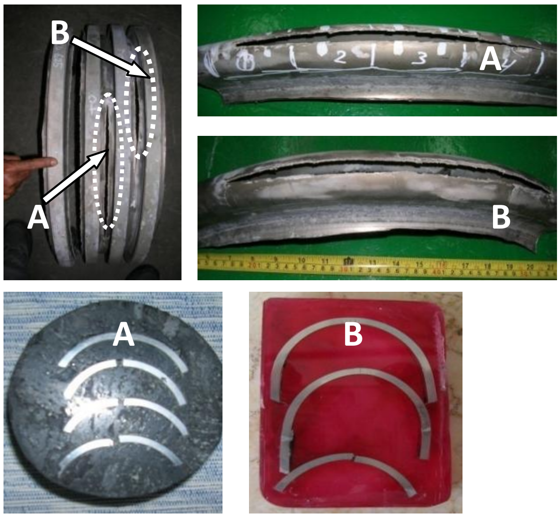
This type of bellows is likely made by applying mandrel, roll forming or hydraulic pressure internally to a tube, forming the convolutions within the corresponding dies. This forming process is usually performed at room temperature and therefore the bellows material experiencing a work hardening and hence its tensile strength, yield strength or its hardness value could increase significantly [2]. In forming high yield strength materials such as nickel-base alloy, an inter-stage anneal may be required. However, annealing is not recommended after forming except in special cases [3-4]. In radial outward forming a small thinning occurs but this is compensated by an increase in yield strength due to cold work (strain hardening). When the bellows are subsequently annealed, the increase in yield is eliminated. Generally speaking that higher yield strength is required to increase fatigue life of the bellows. The argument for annealing usually revolves about stress-corrosion cracking (SCC). However, tests have shown that the threshold of stress required for stress corrosion is very low and the normal pressure stress in an annealed bellows exceeds this level [3-4]. In addition, the work hardening of austenitic stainless steel induced during forming of convolutions generally improves the fatigue life of an expansion joint, often to a marked degree, thus it is not normally considered beneficial to either stress relieve or anneal after forming [5-6].

The purpose of this failure analysis has been to verify the material properties and to determine whether the material used for the expansion bellows met the specification or suitable for its operating condition, and to establish the type, cause and mode of failure of the ruptured bellows of the pre-heater, and based on the determination, some corrective or remedial action may be initiated that will prevent similar failure in the future.

METALLURGICAL INVESTIGATION

In this failure analysis, the ruptured bellows shown in Fig.2 was dismounted from the pre-heater shell and used for laboratory examination. Two ruptured bellows convolutions (A and B) as indicated in Fig.3 were further cut away for samples preparation.

A number of laboratory examinations were then performed on the prepared samples. Macroscopic examination on fracture surfaces of the ruptured bellows convolutions was performed using a stereo microscope at various magnifications, whereas chemical analysis on the ruptured bellows material was carried out using an optical emission spectrometer. The purpose of this chemical analysis performed was to determine whether the material used for the ruptured expansion bellows met the specification or suitable for its operating condition. Specimens for metallographic examination were sectioned from the ruptured bellows convolutions at different locations and subsequently mounted using epoxy and prepared by grinding, polishing and etching, see Fig.3. The photomicrographs were obtained using an optical light microscope at various magnifications. A hardness survey was also carried out on the same samples for the metallographic examination using Vickers hardness method at a load of 5 kg (HV5). Furthermore, examination on some fracture surfaces of the ruptured bellows convolutions was also performed using a scanning electron microscope (SEM) to determine the fracture topography and nature of the failure. This SEM examination was equipped with an EDS (energy dispersive spectroscopy) analysis to detect the presence of any viable defect or corrosion by-product.



Specimens for metallographic examination

Figure 3. Two ruptured bellows convolutions (A and B) as indicated were cut away for samples preparation, and the as polished and etched specimens obtained are seen on the right hand side.

RESULTS AND DISCUSSION

Visual and Macroscopic Examination

From Figs.2 and 3, it can also be seen that four of five bellows convolutions were apparently ruptured or burst. From the four ruptured bellows convolutions, one bellows convolution as indicated in Figs. 2 and 3 is seen to have been experiencing severity of cracking as the fracture area or crack length had reached about fifty percent of the bellows circumference. By considering the difference in fracture area or crack length of the four bellows convolutions, most likely the rupture occurred on the bellows was not at once (or at one event), but in four consecutive sequences within seconds starting from one bellows convolution, and then followed by the second and third bellows convolutions, and finally the fourth bellows convolution. Most of the crack rupture was found to form on the outer bend or radial outward convolutions, and none was found to form on the inner bend or radial inward convolutions (see also Fig.4). This may be caused by the difference in stress conditions in both side, the outer bend convolution was subjected to tensile bending stress, while the inner bend convolution was subjected to compressive bending stress. In addition, most of the crack rupture took place on the upper or top side section of the bellows convolutions. No any cracking was found in the lower or bottom side section of the bellows convolutions.

As seen in Figs.3 and 4, most of the fracture surfaces of the ruptured bellows convolutions exhibit stepwise cracking path with little or no ductility. This indicates that most of the cracks occurred on the ruptured bellows convolutions had propagated in brittle manner. In addition, the fracture surfaces shown in Fig.4 generally reveal brittle pattern with flat facets and form stepwise or jump cracking path as indication of crack propagation. It is also clearly seen that most of the cracks were originated from small pits formed on the inner surface or inner wall of the bellows convolution and propagated outward in a brittle manner. This was indicated by formation of several or multiple parallel shallow cracks with some branching. Shortly after the crack reached the outer edge or outer surface of the outer bend bellows convolution, a fast crack grew rapidly through the remaining section. The rough surface left by the fast crack near the outer surface of the bellows convolution is final fracture overload which appears in ductile manner. It can also be seen from the fracture surfaces shown in Fig.4 that the final ductile fracture overload is much smaller than the brittle crack propagation zone. This may indicate that the fracture pattern of the ruptured bellows convolution was produced by a low nominal stress, probably much below the yield strength of the bellows material [3-4]. In addition, most of the fracture surfaces shown in Fig.4 are rough in appearance and may be containing with some corrosion product or deposits as the fracture surfaces were discolored due to reaction with the environment such as steam containing some corrosive agent [5].

Chemical Analysis

Results of the chemical analysis obtained from the material used for the ruptured expansion bellows in comparison with the standard material are presented in Table 1.

It can be seen that most of the elements content of the ruptured expansion bellows approximately met to the material specification of Inconel 625 or Alloy 625, except the Cr content which is relatively low in comparison with the standard material of Inconel 625[1]. It was not clearly known what impact could be caused by this low chromium content, but in general the nickel-base alloys containing high chromium would be required in order to increase their resistance to corrosion.

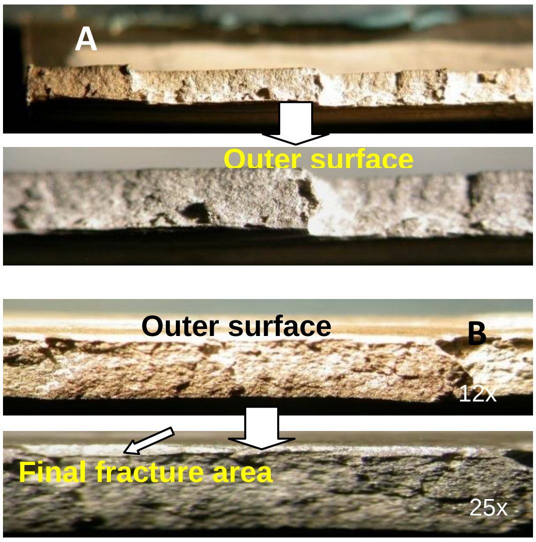


Figure 4. View of some fracture surfaces of the ruptured bellows convolutions A and B at their outer bend convolutions

Due to its low Cr content, the ruptured bellows material which was initially designed to use Inconel 625 may have reduced its corrosion resistance. Inconel 625 or Alloy 625 is a nickel-chromium-molybdenum alloy with an addition of niobium that acts with the molybdenum to stiffen the alloy's matrix and thereby provide high strength without a strengthening heat treatment. The alloy resists a wide range of severely corrosion environments and is especially resistant to pitting and crevice corrosion [1].

Metallographic Examination and Analysis

Microstructures obtained from all samples of the ruptured bellows convolution A are very much similar one to the other. Some microstructures obtained from location at right hand side section around the main crack rupture are presented in Fig.5. Most of the microstructures obtained obviously exhibit multiple parallel cracks that were most likely originated from some small pits formed on the internal surface of the outer bend convolution and subsequently propagated to form extensive branching in intergranular manner through the austenitic

Table 1. Results of chemical analysis of the ruptured bellows material of the pre-heater in comparison with the standard material

Element	Composition, wt - %			
	Ruptured Expansion Bellows	Standard Material (1)		
		Inconel 625	Inconel 600	Alloy 625
Ni	67.900	61.0	76.0	58.0 min
Cr	15.500	21.5	15.5	20.0 – 23.0
Mo	8.210	9.0	-	8.0 – 10.0
Nb	3.200	3.6	-	3.15 – 4.15
Al	0.180	0.2	-	0.40 max
Ti	0.215	0.2	-	0.40 max
Fe	4.230	2.5	8.0	5.0 max
Mn	0.120	0.2	0.5	0.50 max
Si	0.050	0.2	0.2	0.50 max
C	< 0.002	0.05	0.08	0.10 max
S	< 0.004	-	-	-
Co	0.083	-	-	1.0 max
V	0.100	-	-	-
W	0.042	-	-	-
Zr	0.020	-	-	-
Ta	< 0.050	-	-	-
Hf	< 0.020	-	-	-
Cu	0.046	-	-	-
Mg	0.005	-	-	-

grain boundaries of the bellows material, typical of a stress-corrosion cracking (SCC)[5]. Similar microstructures shown in Fig.5 were also obtained from the other sample located at right hand section at some distance away from the main crack rupture, see Fig.6. However, the cracks that were formed at some distance away from the main crack rupture appear to be less extensive as the tensile bending stress in this area was probably lower than the bending stress formed around the main crack rupture area.

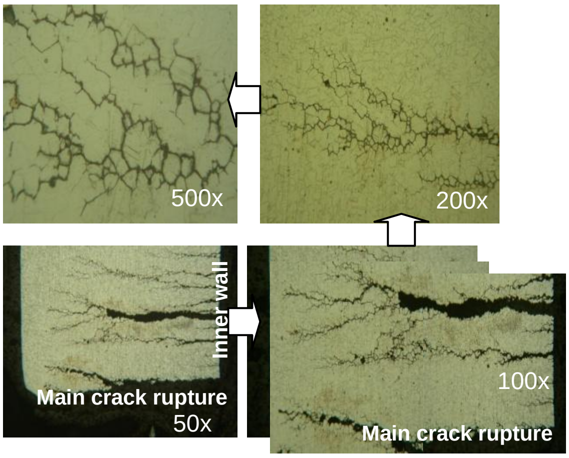


Figure 5. Microstructures obtained from some location of the ruptured bellows convolution A at right hand side section around the main crack rupture

Microstructures obtained from some sample located at left hand side section of the main crack rupture were also very much similar to those obtained from the right hand side section of the main crack rupture of the bellows. Most of the cracks formed around the main crack rupture were generally more extensive in comparison with the crack formed at some distance away from the main crack rupture area. The difference in crack severity as described above may be associated with the difference in stress level occurred on both area. Area subjected to a higher tensile stress level generally experienced more extensive crack compared to that area of lower tensile stress level. As also seen in Fig.7, a small portion at the final fracture area of the bellows convolution exhibits some plastically deformed microstructures with ductile appearance, although at most part of the fracture surface appeared brittle. This indicates that the SCC in bellows convolutions had propagated in brittle manner under a low nominal stress, while the final fracture area exhibits some ductile fracture overload. This may also indicate that the threshold stress for this SCC to occur was relatively low. This threshold stress is generally a function of temperature, the composition and metallurgical structure of the alloy, and the composition of the environment. In some tests, cracking could occur at an applied stress as low as approximately 10% of the yield strength; for other metal-environment combinations, threshold stress is approximately 70% of yield strength [3-4,6].

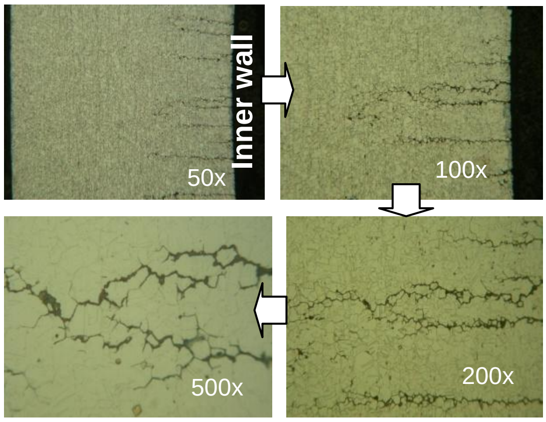


Figure 6. Microstructures obtained from some location of the ruptured bellows convolution A at right hand side section at some distance away from the main crack rupture area

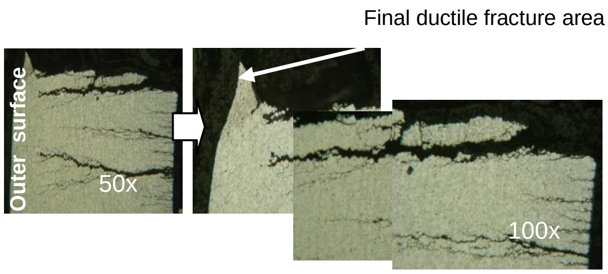


Figure 7. Microstructures obtained from some location of the ruptured bellows convolution A at left hand side section around the main crack rupture area, showing some small portion of the final ductile fracture overload

In order to obtain some further confirmation on the failure type and mode that may have occurred on the ruptured bellows, other metallographic examination was also performed on some sample of the ruptured bellows convolution B and the results obtained are presented in Fig.8. Macrostructures shown in Fig.8 also clearly exhibit multiple parallel cracks propagated in intergranular manner with extensive branching especially in area of bellows convolutions that were subjected to high tensile bending stresses. On the other hand, in area of bellows convolution having less or no tensile bending stresses, formation of cracks became less significant and the damage appeared to be predominant intergranular corrosion. The corresponding microstructures shown in Fig.8 confirm that area having higher tensile bending stresses generally exhibited an intergranular stress-corrosion cracking (IG SCC) pattern with more extensive crack branching, while area having less or lower tensile bending stresses generally exhibited a predominant intergranular corrosion (IG corrosion). The formation of these IG SCC and/or IG corrosion indicates that the ruptured bellows material which was made of Inconel 625 had been experiencing sensitization due probably to some carbides or second phase precipitation in the austenitic grain boundaries[6]. The lower Cr content found in the bellows material shown in Table 1 may have also to some extent contributed to the lowering of the corrosion resistance of the bellows material.

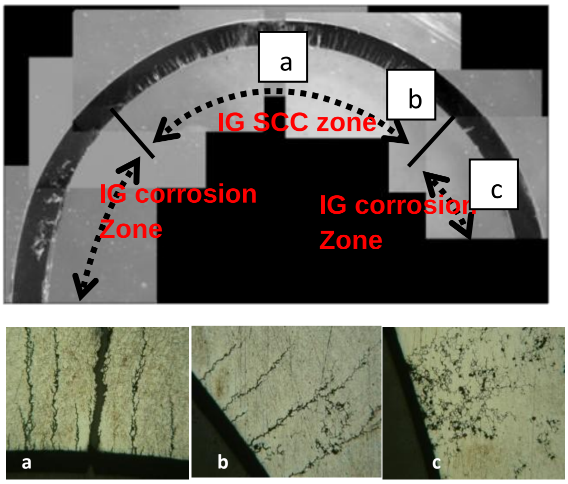


Figure 8. Macrostructures obtained from some specimen of the ruptured bellows convolution B and the corresponding microstructures at different test locations as indicated

Hardness Test and Analysis

A hardness survey was carried out on all specimens of the ruptured bellows convolutions A and B using Vickers hardness method at a load of 5kg (HV5). The average hardness values obtained from all specimens are in the range of 324.0 to 337.2 HV or equivalent to 307.0 to 320.0 HB, or 32.5 to 34.0 HRC. According to the standard material of Inconel 625 in the form of annealed sheet or strip, its average hardness values are in the range of 145 - 240 HB (or 77-100 HRB), where 100 HRB ≈ 22.7HRC[7]. From the above comparison, it can be seen that most of the hardness values obtained from the ruptured bellows material in average are much higher than the hardness value of the standard Inconel 625 in the form of annealed sheet or strip. This indicates that the high hardness values obtained from the ruptured bellows convolutions were most likely associated with the strain hardening occurred during the forming process of the bellows at room temperature in which no any subsequent annealing process was likely performed. This strain hardening due to cold work is generally required in compensating of thinning occurred on the bellows convolutions in order to improve its fatigue life, but the resulting high hardness value may have contributed to the increased tensile residual stress and hence could promote the bellows material susceptible to SCC [2-4].

SEM Fractography and EDS Analysis

The SEM photofractographs obtained from fracture surfaces of the ruptured bellows convolutions A and B are presented in Fig.9. Most of the intergranular stress-corrosion cracking (IG SCC) of the ruptured bellows material have the classic rock candy appearance, typical of brittle fracture pattern. These SEM photo fractographs further confirm that the ruptured bellows material was most likely subjected to embrittlement during operation caused by grain boundary separation.

The deposits that may have been present at the fracture surfaces of the ruptured bellows convolutions were analyzed using the EDS technique, and the results obtained are presented in Fig.10. The deposits contained major elements of Ni, Cr, Fe, Mo, C and O, plus minor elements of Al, Ti, Mn and Si. In addition, the deposits also contained some trace elements of Na, Cl and K.

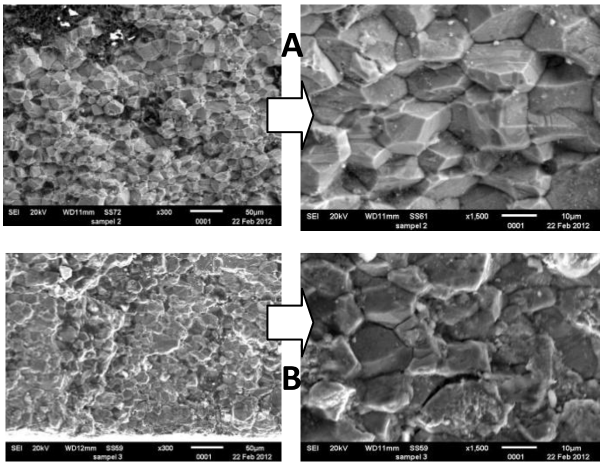
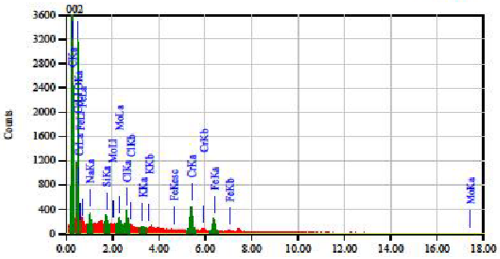


Figure 9. SEM photofractographs obtained from the fracture surfaces of the ruptured bellows convolutions A and B

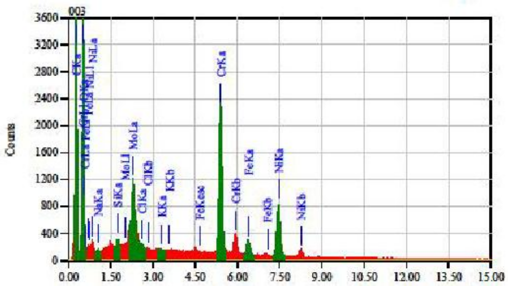
From the results of EDS analysis obtained, it can be said that Ni, Cr, Fe, Mo, Si, Al, Ti and Mn are the base metal constituents of Inconel 625. The other deposit constituents such as Na, Cl and K may have entered into the pre-heater as trace elements in the shell side steam due to accidental carry-over of dissolved solids, or being trapped in the bellows convolutions after the pre-heater had been periodically cleaned by chemical solution containing such trace elements. Due to its disadvantage in shape and geometry of the bend curvature of bellows convolutions, a lot of fluid was probably allowed being trapped in the corrugations and therefore such trace elements could become concentrated in some particular area especially in the upper or top side of the bellows convolutions where alternating wet and dry conditions were probably present. Other possible source of the trace element present may have been likely coming from the use of any contaminated water during the hydrostatic testing [8]. From the EDS results shown in Fig.10, most likely sodium (Na) was the predominant trace element that may have caused the expansion bellows of the pre-heater susceptible to a caustic induced stress-corrosion cracking (SCC). The presence of Na that was responsible for SCC may have not been in large quantity or in high concentration[5,9]. The operating temperature of steam used (265 °C) in the pre-heater may have further activated the process essential to SCC. In addition, other traces of element such as Cl and K, although their presence were considered not significant, but to a limited extent they may have also contributed to the failure of the bellows convolutions. Chloride (Cl) may have influenced to the formation of corrosion pits at the sites where the SCC may have been originated, whereas potassium (K) may have participated to further increase in the caustic concentration[5].

From the previous results obtained, it was also found that SCC was not always initiated from the corrosion pits due to the presence of chloride (Cl), but some were initiated even on smooth surface of the bellows convolution. This indicated that the environment was sufficiently corrosive and high tensile stresses were present. Moreover, the crack propagation rates may have increased dramatically as the bellows material may have been experiencing sensitization due to formation of carbides or second phase precipitation at the austenitic grain boundaries that caused the bellows material susceptible to intergranular attack [5-6]. This condition could significantly lower the grain boundary strength and the bellows material was prone to embrittlement due to grain boundary separation, especially in the presence of sodium (Na) or caustic solution in the steam of 265 °C temperature. Due to this caustic embrittlement, the threshold of stress for intergranular SCC to occur was most likely much below the yield strength of the bellows material [3-4,6]. This was supported by the fact that the remaining section of ductile final fracture area of the bellows convolution was very much smaller than the brittle crack propagation area. Other contributing factor that may also have caused the bellows material susceptible to SCC or embrittlement was likely due to high hardness of the bellows material.



Element	Mass (%)	Atom%
C	51.46	61.00
O	41.22	36.69
Na	0.87	0.54
Si	0.29	0.14
Cl	0.58	0.23
K	0.11	0.04
Cr	2.63	0.72
Fe	2.04	0.52
Mo	0.82	0.12
Total	**100**	**100**

(a)



Element	Mass (%)	Atom%
C	41.21	58.91
O	30.27	32.49
Na	0.19	0.14
Si	0.25	0.15
Cl	0.11	0.05
K	0.03	0.01
Cr	12.81	4.23
Fe	1.90	0.58
Ni	9.31	2.72
Mo	3.93	0.70
Total	**100**	**100**

(b)

Figures 10 (a) and (b). EDS spectrum of elements obtained from the fracture surface deposits of the ruptured bellows convolutions A and B (continued)

CONCLUSIONS

From the results of failure analysis obtained, a number of conclusions can be drawn as follows:

1. The material used for the ruptured expansion bellows of the pre-heater was found not completely met to the material specification of Inconel 625, although most of its alloying elements approximately close to the material specification, but the chromium content was found relatively lower compared to the standard material of Inconel 625 or Alloy 625. In addition, hardness value of the bellows material was found quite high (32.5 - 34.0 HRC), and this might be influenced by strain hardening induced during the forming of bellows convolutions with no any subsequent annealing was probably performed. This high hardness may have increased the presence of tensile residual stress which could promote the bellows material susceptible to stress corrosion cracking (SCC).
2. According to the fracture topography and mode of failure, the ruptured expansion bellows of the pre-heater had experienced predominantly to stress-corrosion cracking (SCC) caused by the simultaneous presence of tensile stresses and a corrosive agent in which sodium was found being the major caustic corroding agent. Most of the SCC occurred were initiated from the inner wall of the outer bend or radial outward convolutions and subsequently propagated outward in intergranular manner with extensive branching through the austenitic grain boundaries of the bellows material. The severity of cracking was very much affected by the level of tensile bending stress present on the bend convolutions, and therefore most of the main crack rupture was found to take place at the peak bend convolutions where the tensile stress was maximum or highest. In some area having less or no tensile stress, the damage pattern was predominantly altered into the intergranular corrosion.

3. Susceptibility to caustic embrittlement in caustic solutions is a function of caustic strength, metal temperatures, stress levels and metal microstructures, and all of these factors were likely in favor to the acceleration of SCC failure for the bellows during its operation.
4. In addition to sodium (Na) as a major trace element, other trace elements Cl and K in relatively lower amount were also identified at the fracture surface deposits of the ruptured bellows convolutions. Both sodium (Na) and potassium (K) were likely responsible in increasing caustic concentration, while chloride (Cl) was likely the cause for formation of some corrosion pits on the internal wall of the outer bend convolutions.
5. Other contributing factor that may also have caused to rapid failure of the bellows was likely due to its disadvantage in shape and geometry of the bend curvature of bellows convolutions allowing a lot of fluid being trapped in the corrugations and therefore traces of caustic could become concentrated in that particular area especially on the upper or top side of the bellows convolutions and resulted in caustic embrittlement thereon.

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