STRESS CORROSION FAILURE OF 304 TYPE STAINLESS STEEL PIPE IN SEAWATER ENVIRONMENT

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ABSTRACT

A stainless steel pipe, type 304, used for cooling exhaust gases in seawater environment failed after only four months of operation. The pipe was badly corroded in areas which came under direct impact action of the exhaust gases. The multiple pitting, cracking and fracturing which occurred in these areas was a result of stress corrosion cracking and a corrosion fatigue mechanism. The sudden cooling induced by splashing seawater produced large internal stresses causing extensive deformation in the form of multiple sliplines. The mode of failure was primarily intergranular with branched short transgranular cracks composed of step-like segments.

KEYWORDS

Stress corrosion; stainless steel; seawater; exhaust gases; intergranular and transgranular corrosion.

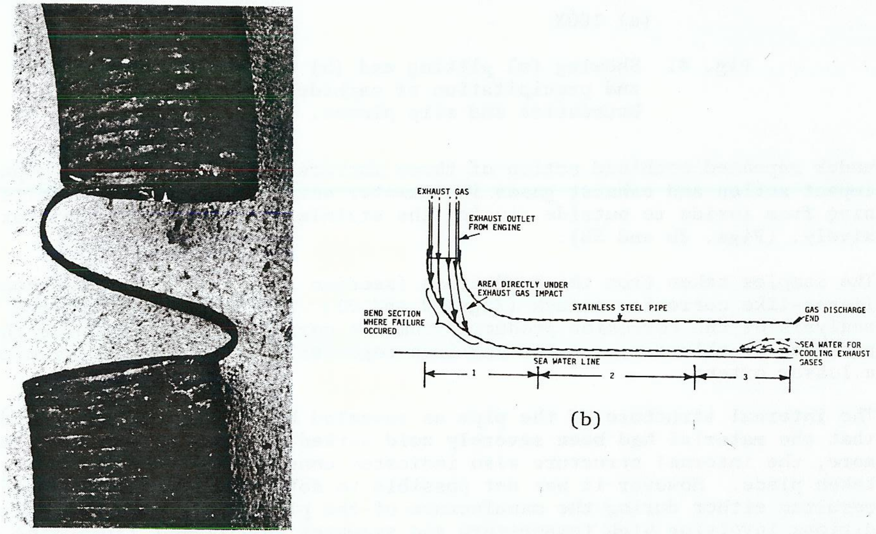
INTRODUCTION

The austenitic stainless steel 300 series having attractive strength, toughness, corrosion resistance and weldability properties, are widely used for marine and other high chloride media applications with reasonable success. The excellent corrosion resistance property of stainless steel 300 series is due to the formation of a passive surface oxide film which is self-healing in an oxidizing environment. As a result, the service life of this material seems to be not a major concern to metallurgists and engineers. However, prolonged contact at high temperature (50°C to 400°C) with water containing chlorides (such as seawater), the steels from this series are subjected to severe pitting or crevice type corrosion, and can lead to catastrophic failure.

The author was recently consulted on the failure of a type 304 stainless steel flexible pipe which was used as an exhaust gas discharge pipe in a marine engine. The pipe, 1400 mm long with 100 mm ID, was connected to the exhaust outlet of a diesel marine engine (Fig. 1b). The discharge-end was about 50 mm above the seawater line. The exhaust gases were cooled by seawater wave-splash action in which seawater could travel up to 300 mm.

OBSERVATIONS

Complete failure occurred in this stainless steel pipe in the area shown in Fig. 1 after four months of operation. The failure was in the form of rust and leaks at the bend-section (Fig. 1b). The temperature in this section often reached 400°C and was under repeated thumping action of the exhaust gases (Fig. 1b). Figure 1 shows a general view of the rusted and fractured section of the stainless steel flexible pipe.



(a)

(b)

Fig. 1. (a) Showing the corroded stainless steel pipe.
(b) Showing layout of the pipe attachment to the engine, discharge end, seawater line damaged areas and samples taken for the investigation (schematic).

Three samples were taken from the failed stainless steel pipe (Fig. 1b). Sample 1 represented the bend-section where failure actually occurred. Sample 2 was about 300 mm from the bend-section, while sample 3 was from the discharged end about 900 mm away from the failed section. The temperature of the bend section (failed section) ranged from 300 to 350°C while outside the surface temperature was about 250 - 300°C. Temperature measured using a recorder showed that it exceeded 400°C.

The failed stainless steel exhaust pipe was analysed chemically (Table 1). The analysis from the three sections indicated that it was 304 type stainless steel with carbon content of 0.051 weight percent. Analysis of seawater is also given in Table 1.

TABLE 1 Chemical Analysis of the Failed Stainless Steel Pipe and Seawater

Failed Stainless Steel Pipe	
Elements	Wt. Percent
Chromium	18.630
Nickel	9.210
Manganese	1.710
Silicon	0.620
Carbon	0.051
Sulphur	0.016
Phosphorus	0.012
Iron	Remaining
Seawater	
Constituents	Amount ppm
Sodium	10,600
Chlorine	18,889
Magnesium	1,282
Calcium	410
SO_4	2,648
HCO_3	140
pH	7.74
Dissolved O_2	5.32 ml/litre

Chemical analysis identified the corrosion products (Fig. 2) from several pits and cracks as $Fe_2O_3.H_2O$ with substantial concentration of chloride, sodium, calcium, nickel and chromium ions.

Macro-examination at low power showed that the pipe was badly rusted in the bend-area (section 1 - Fig. 1b) with a reddish-green-blueish appearance. This is a form of corrosive attack found in the high chromium-nickel alloy and is called "green rot" because of its appearance. This occurs most frequently in cases where the metal has been exposed to carbonaceous gases or flue gases at high temperatures in the presence of chlorides and sulphates.

Samples from section 1 (bend-area, Fig. 1b) of the pipe that had failed were examined at low magnifications (50 to 100X). Extensive cracking and pitting was found (Fig. 2). Most of the pits were 50 to 2000 microns in diameter. In several areas the pitting was severe, several pits were joined together giving the appearance of cracks. Cracks were running from inside edge to outside (Fig. 2b).

METALLOGRAPHIC EXAMINATION

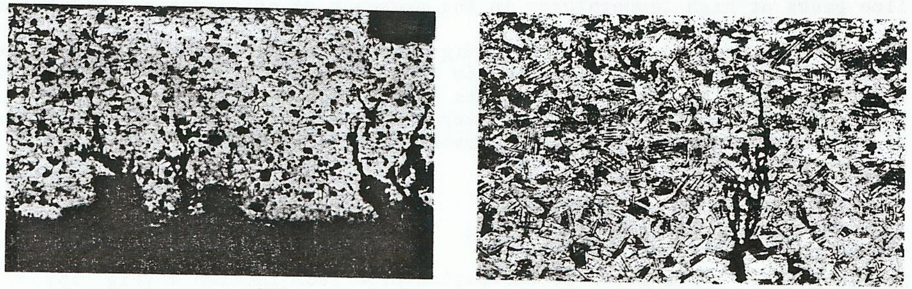
Metallographic examination of the failed pipe from section 1 (Fig. 1b) revealed that the average penetration of the pits and cracks were through the wall of the pipe (Figs. 2 and 3). Some pits and cracks formed "caverns" where penetration was complete (Fig. 3b).

The microstructure from sections 2 and 3 showed well defined annealed equi-

(a) Cracking in a Zig-zag mode (b) Showing severe intergranular cracking

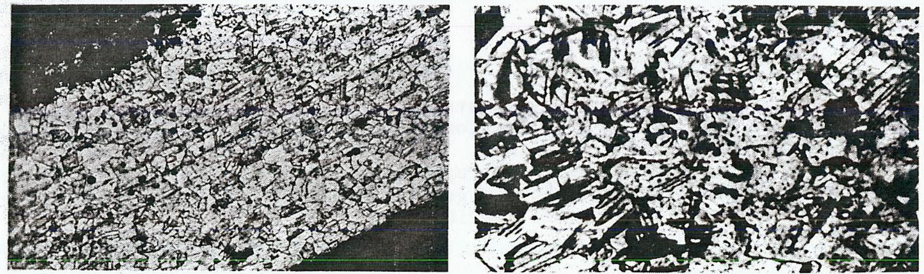
Fig. 2. Pattern of corrosion cracking in the failure areas. Unetched. 100X.

axed grains with extensive pitting and carbide precipitation. This clearly indicated some degree of sensitization had occurred (Fig. 4). The deformation lines (slip lines) strongly indicated the presence of internal stresses caused by repeated action of heating and cooling by seawater. The x-ray diffraction analysis strongly indicated that the precipitates at the grain boundaries and slip lines were to be $M_{23}C_6$ (chromium carbide). The precipitation of chromium carbides in the grain boundaries and slip lines caused matrix to deplete in chromium content. The chromium depleted matrix areas were attacked by the chloride ions under impact type action of exhaust gases at high temperature causing formation of small pits. These small pits under high temperature in the repeated impact action of engine exhaust gases in seawater (chloride, sulphate etc) environment acted as nuclei to form intergranular and transgranular cracks (Fig. 5). These cracks were propagated under repeated combined action of three factors (high temperature, repeated impact action and exhaust gases in seawater environment(by joining pits running from inside to outside causing the stainless steel pipe to leak extensively. (Figs. 2b and 5b).



(a) (b)

Fig. 3. (a) Showing fingerlike corrosion; (b) Transgranular and intergranular corrosion cracking. 100X.

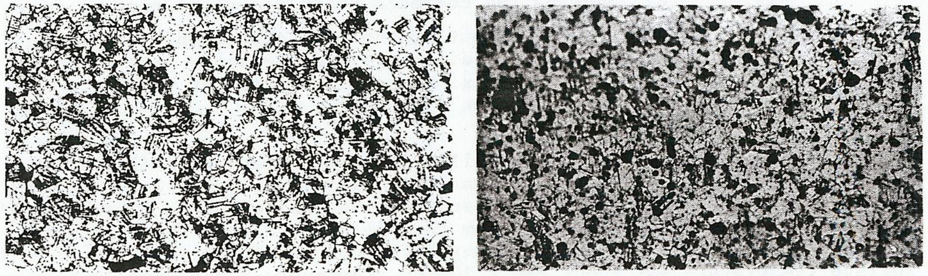


(a) 100X (b) 500X

Fig. 4. Showing (a) pitting and (b) deformation lines and precipitation of carbide particles on grain boundaries and slip planes.

The samples taken from the bend-areas (section 1, Fig. 1b) showed extensive finger-like corrosion attack (Figs. 2 and 3). The electron microprobe analysis of the corrosion products from the corrosion fingers showed the presence of chloride, sulphur and iron together with nickel and chromium to a lesser extent.

The internal structure of the pipe as revealed by micro-examination indicated that the material had been severely cold worked (Figs. 4, 5 and 6). Furthermore, the internal structure also indicated considerable work-hardening had taken place. However it was not possible to determine whether this had resulted either during the manufacture of the pipe or from the service conditions involving high temperature and seawater environment (including sudden quenching effect), combined with the fluctuating pressure exerted on the pipe



(a) (b)

Fig. 5. (a) Showing extensive pitting on the grain boundaries and within the grains. 100X.
(b) Showing crack nucleation from the pits. 100X.

by the release of the exhaust gases from the engine (Figs. 4, 5 and 6). However experiments were conducted simulating the situation which would be reported at a later date.

DISCUSSION

Very little has been published on the stress corrosion cracking of stainless steel-type 304 resulting from the impact action of exhaust gases at high temperature in seawater environment. Under normal conditions this type of stainless steel is not very susceptible to stress corrosion cracking.

Microstructures from all sections exhibited cracking, pitting and carbide precipitations. The section 1 showed extensive cracking (Figs. 2, 3, 4 and 6). Carbide precipitation was found around the grain boundaries and within the grains (Figs. 4 and 5).

In section 1 (Fig. 1b) cracks followed the grain boundaries with branching out in the grains. Such microstructures could only exist if the material was heated to high temperatures and cooled suddenly. This seemed to have happened here. The high internal stresses which resulted from repeated actions (i.e. impact action of the exhaust gases together with seawater quenching from high temperatures), were found to be in order of 10 kgt/mm^2 in the bend areas while areas away from the bend, the stress when measured using strain gauges was only 2 kgt/mm^2.

Furthermore, since the crack (Fig. 6) propagation showed a step-like growth, the question also arose as to whether these cracks should be considered as corrosion fatigue cracks produced by constant impact action of exhaust gases with seawater quenching effect from high temperatures.

Fig. 6. Showing branched transgranular and intergranular stress corrosion cracking and slip lines in the failed areas. 500X.

Since these cracks were intergranular and transgranular propagating in a step-like manner, the failure seemed to be due to a combination of stress corrosion cracking and corrosion fatigue mechanism. Furthermore, when pitting and stress corrosion cracking appear together, the SCC cracks originate from the pits and tend to run out of the pits (Figs. 4, 5 and 6). This can be reasoned by the increase chloride and sulphur concentration in the pit compared to that of the surrounding areas. Figures 4, 5 and 6 clearly show the stress corrosion cracks running from the pitted areas.

In austenitic steel, the SCC cracks run in straight lines following the grain boundaries and branch out at sharp angles towards the grains (Figs. 3 and 6).

CONCLUSION

The fracture of stainless steel pipe was the result of stress corrosion cracking and corrosion fatigue under repeated impact type load exerted by the sudden discharge of exhaust gases at high temperature in seawater environment.

This triple action treatment (high temperatures, impact type discharge of exhaust gas in seawater environment and sudden cooling) caused chromium carbide to precipitate at the grain boundaries depleting chromium in areas adjacent to grain boundaries. The depleted matrix was selectively attacked by halide ions causing extensive pitting. These pits under the influence of triple action (stated above) grew, coalesced and turned into cracks. These cracks propagated under the influence of high internal stresses and chloride ions attacks fracturing the stainless steel pipe transgranularly and intergranularly.

Frequent heating-cooling cycle induced high thermal stressing causing chromium carbide to precipitate and pits to form in the chromium depleted areas. Corrosion pits acted as nuclei in the formation of multiple pitting, cracking and fracturing the pipe in the bend section.