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Steve Adair
TAQA

In-service stress corrosion cracking of AISI 316L stainless steel in an H_2S environment

S. T. Adair* and P. A. Attwood

Since publication of ANSI/NACE MR0175/ISO 15156 in 2003 there has been much debate on the performance of austenitic stainless steels in oil and gas production environments, with researchers recommending relaxation of the ISO 15156 restrictions for this material. This paper describes a recent austenitic stainless steel stress corrosion cracking failure and discusses its implications for the current restrictions of the ISO standard and recently proposed relaxations of these restrictions.

Keywords: Hydrogen sulphide, Sulphide stress corrosion cracking

Introduction

In July 2011 a leak from a 2' diameter pipe to a pressure safety valve was reported in an acid flash gas compression plant. Over a two day period, two additional leaks in similar lines on adjacent compressors were reported.

A root cause of failure assessment concluded that the failures were caused by sulphide stress corrosion cracking enhanced by the presence of chlorides. High ambient temperatures occurring in the summer months, resulting in discharge temperatures from the compressor after cooler rising above 60°C were regarded as a significant contributory factor. Moreover, although the failed pipes had seen four years of service, all three failures occurred over a period of just two days, and so it was suspected that the cracking may have been accelerated by water washing of the discharge coolers which resulted in short (up to 2 h) temperature excursions up to 90°C.

This paper describes the nature of the failures and discusses how the findings may contribute to the ongoing debate over the ISO 15156 restrictions for austenitic stainless steels.

Failure description

Over the course of two days, three leaks were reported in two upstream pressure safety valve flare tail pipes on adjacent compressor trains (the failures occurred in line shown in red in Fig. 1).

Each failure occurred at a pipe to elbow weld in a horizontal section of the line, with the leak situated in the heat affected zone (HAZ) of the weld (Fig. 2), and in top section of the pipe.

Initial *in situ* visual examination indicated fine pitting on the external surface but radiographic examination was inconclusive. All sections containing failures were removed for metallographic examination (Fig. 3).

KPO, Karachaganak, Kazakhstan

*Corresponding author, email AdairS@kpo.kz

Metallographic investigation

Visual examination of the failed component in the as received condition showed the presence of black deposition covering the lower half of the pipe, which is probably an indication of the accumulation of liquids in the horizontal section of the line. Black surface deposits were also present for the full circumference of the pipe for a band about an inch either side of the weld.

Microscopic examination in the as received condition identified the presence of cracking on the outside surface (Fig. 4), with a hair-line crack extending about 13 mm from the weld edge into the straight pipe at an angle of about 30°. Cracking was also visible internally, starting at the fusion boundary of the weld. However, thick and tenacious corrosion product obscured much of the crack.

After cleaning in dilute nitric acid solution to remove the black corrosion product, the internal cracking was visible to the naked eye (Fig. 5). The crack appears to start at the fusion boundary, close to a start–stop location in the weld root. From this location the crack runs along the fusion boundary in one direction, into the straight pipe in the other direction, as well as crossing the weld and running at 90° to the weld into the elbow.

Sections removed for examination contained a total of eight welds, of which three were known to have leaked in service. However, metallurgical examination showed that all eight welds had suffered cracking. Cracking was more severe in the upper section of the weldments, although the cracking in the leaking weld extended full circumference.

Macrophotographs show that whilst the most severe pitting and cracking occurred in the weldment, it was also present in the parent material (Fig. 6).

Cracking is predominantly intergranular with some branching, exhibiting a morphology typical of stress corrosion cracking (Fig. 7).

Hardness survey

Results of a hardness survey performed on the failed weldments are provided in Table 1. All hardness results are within the limits of ISO 15156.

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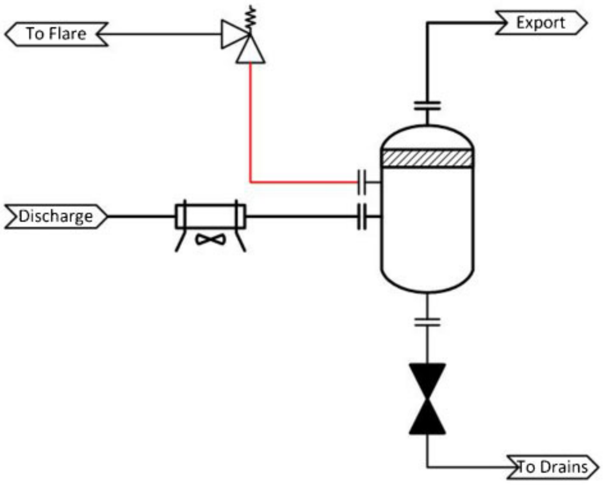
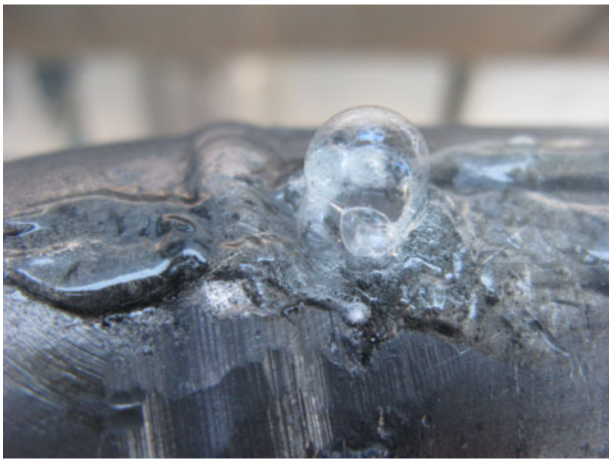
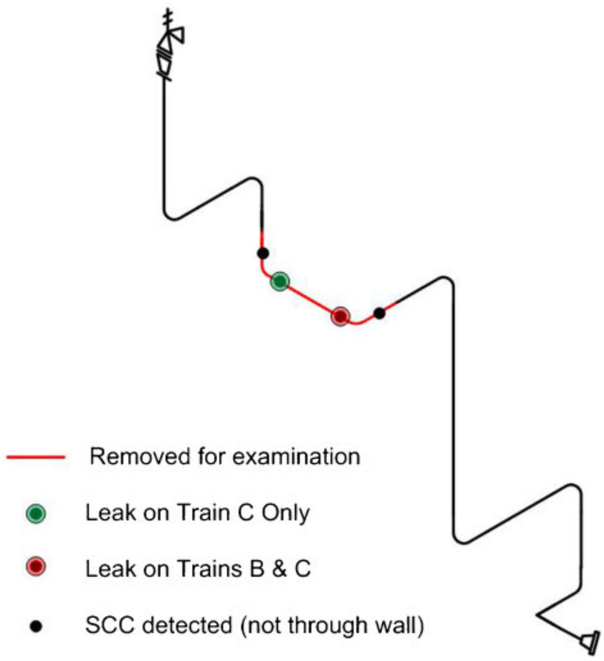


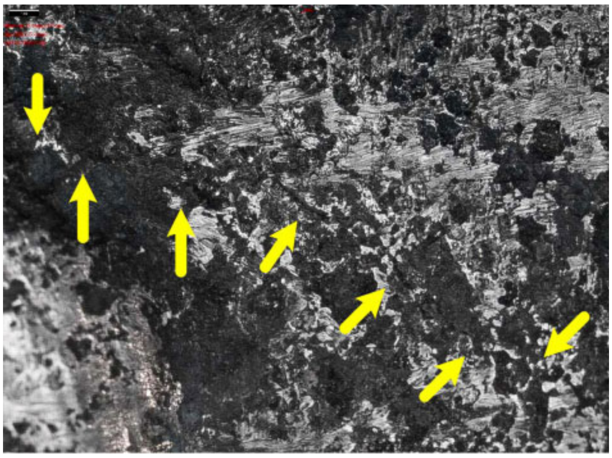
1 Process schematic showing failure location



2 Leakage occurred at elbow to pipe weld, with leak occurring in HAZ



3 Isometric showing locations where leaks occurred together with section of pipe removed for metallurgical examination



4 Crack viewed from external surface of pipe

SEM analyses

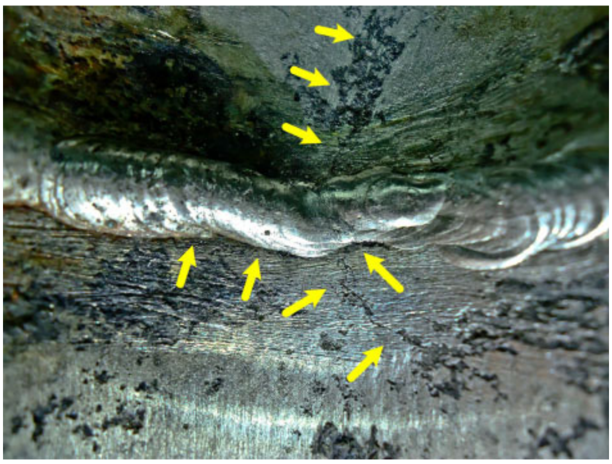
SEM examination included EDX analysis of corrosion products at the internal surface (see Fig. 8) and deep within the cracks (see Fig. 9). High levels of sulphur were detected at both locations. These findings are consistent with sulphide cracking.

Root cause of failure

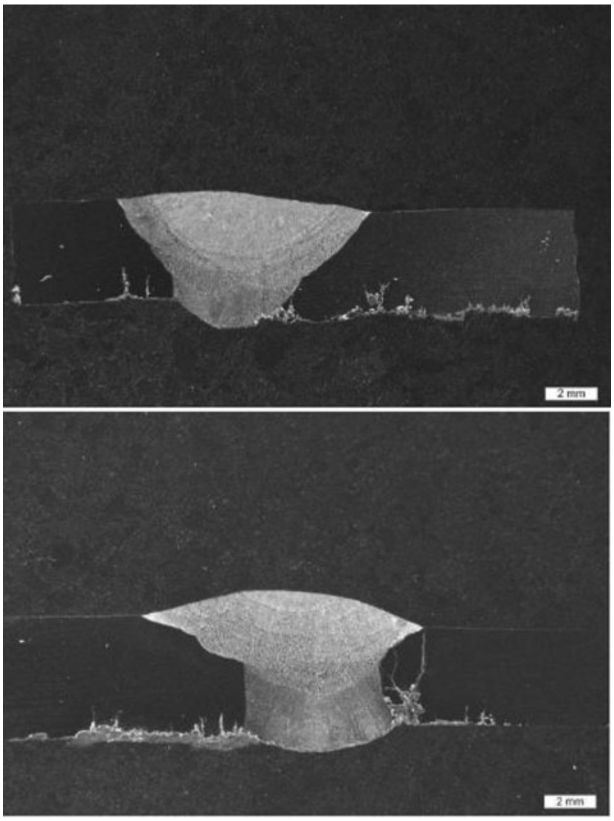
Flash gas from the compressor discharge contains approximately 11 mol.-% H_2S (5·5 bar partial pressure) and is saturated with water, with the condensed water having a chloride content varying between 260 and 900 ppm. Solids extracted from inside the failed pipes contained up to 1300 ppm of chloride.

The normal operating temperature of the compressor discharge drum is 52°C (which is a slightly below the ISO 15156 threshold for austenitic stainless steel in the presence of chlorides).

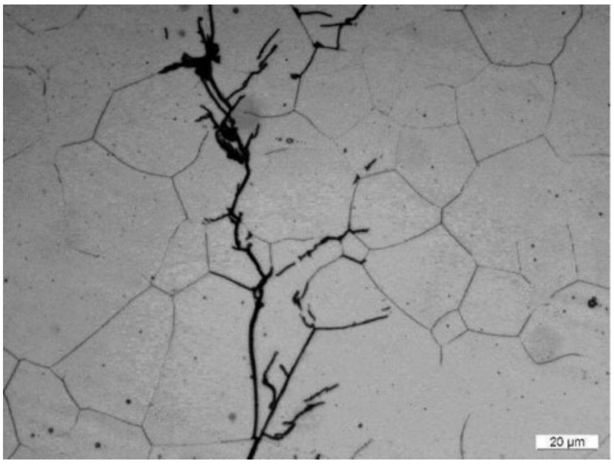
Summer ambient temperatures may rise to 40°C, compromising the efficiency of the compressor discharge cooler and resulting in increased temperatures at the discharge drum. The situation is exacerbated further by excessive fouling of the external tube fins with airborne



5 Following chemical cleaning cracking was visible with naked eye. Crack runs from weld fusion line into parent metal, and also along fusion boundary



6 Macrophotographs showing both pitting and cracking

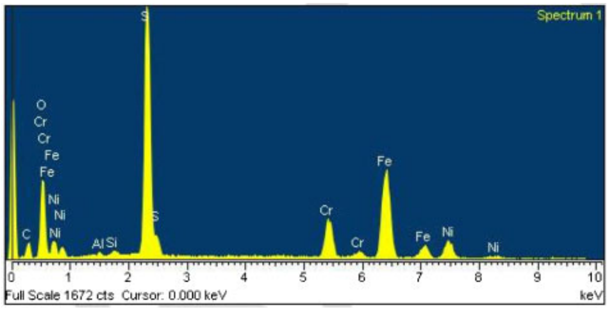


7 Optical micrograph of cracking showing characteristic typical of stress corrosion cracking

dust due to the dry environment. Consequently, operating practice is to wash the fins with water; a procedure which takes approximately 8 h per cooler bay (there are

Table 1 Hardness results/HV10

Location	Hardness
Pipe	163–187
Pipe HAZ	181–183
Weld metal	165–172
Elbow HAZ	192–194
Elbow	178–179



8 Chemical analysis of corrosion products at internal pipe surface (S measured at 25 wt-%)

two cooler bays per cooler). During this procedure the cooler fans are switched off, resulting in a high temperature excursion for the duration of the procedure. Following the washing operation the heat transfer of the exchanger is improved and cooler discharge temperatures are achieved (Fig. 10).

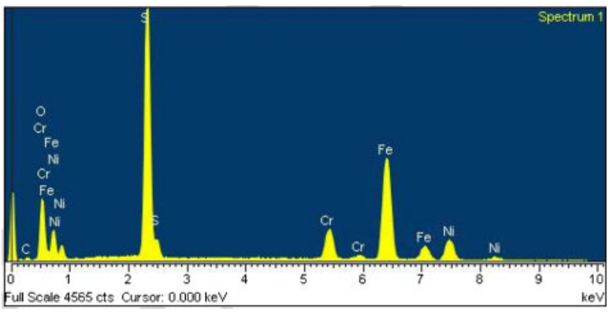
In 2011 a fourth oil and gas train was commissioned. However, commissioning difficulties associated with the acid flash gas compressor resulted in the acid flash gas from the new train being diverted to the pre-existing trains. The increased flow to these trains resulted in increased temperatures, with the average temperature of the discharge from the coolers rising above 60°C (Fig. 11) and the high temperature excursions associated with the washing operations also rising.

The 2011 washing operations were performed on Train A first, followed by Train C, and finally Train B. Thus, Train A experienced the sustained high temperatures for the shortest period, and significantly, no leaks were discovered on this train. Train B experienced the sustained high temperatures for the longest period, and significantly the Train B was the first to failure and exhibited the most extensive cracking.

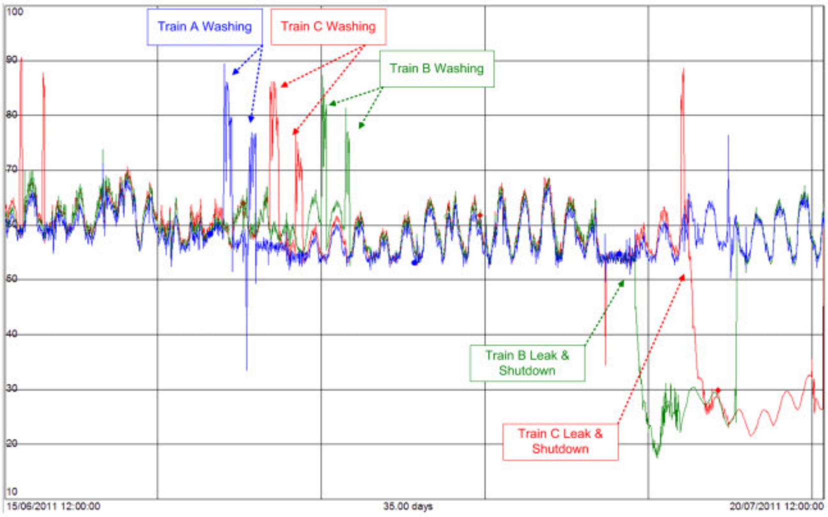
As three through wall failures occurred in a matter of a few hours, a root cause of failure analysis concluded that the failure mechanism may have been accelerated due to the average operating temperatures exceeding 60°C.

Implications for use of ISO 15156

When first published in 2003, ISO 15156[1] restricted the use of austenitic stainless steels such as AISI Type 316L to 60°C maximum when chlorides exceed 50 ppm. This restriction has been the subject of some debate.[2,3] Observations from laboratory tests conducted by both Trillo and Kane[3] and Holmes and Bond[2] indicated the



9 Chemical analysis of corrosion products inside crack (S measured at 19 wt-%)



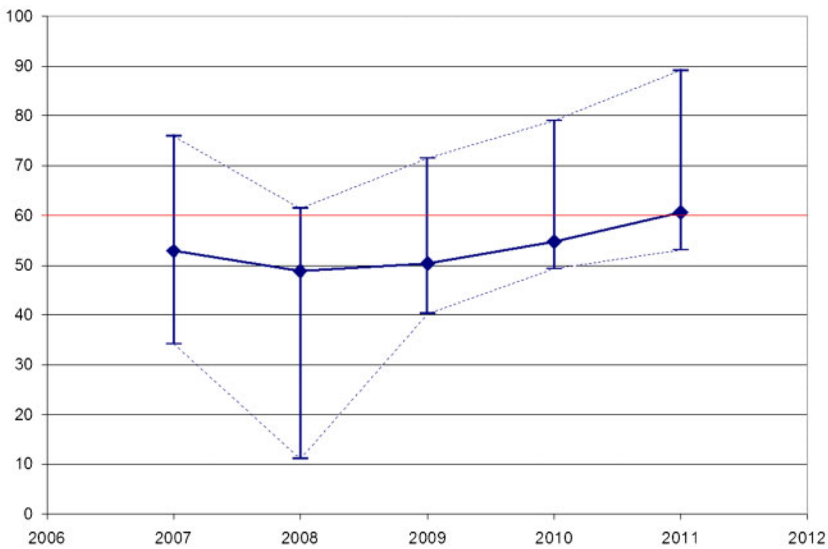
10 Cooler discharge temperatures showing washing operations and times of failure

acceptability of austenitic stainless steels and their weldments under environments which are significantly more severe than the original ISO 15156 restrictions. Following a ballot in 2007,[4] the restrictions for AISI 316 materials were revised in a technical circular[5] and subsequently endorsed in the 2009 version of the standard.[6]

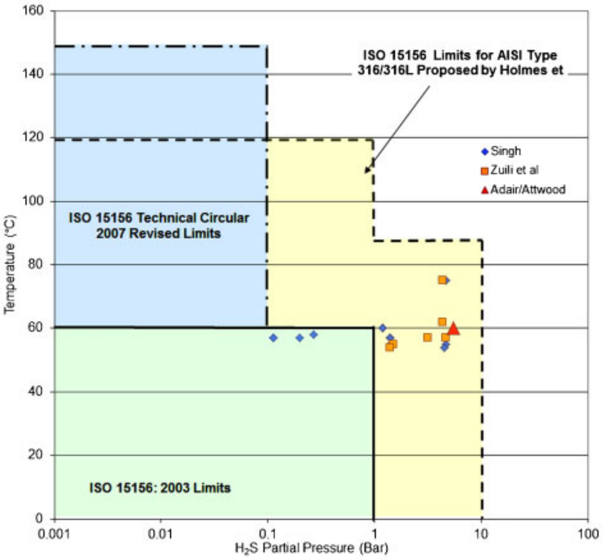
The failures reported in this paper occurred in an environment which is classified as susceptible under the current ISO 15156 restrictions, but would be classified as 'non-susceptible' under further recently proposed relaxations. Moreover, the failures reported in this paper are not unique, with industry reporting several previous failures within the proposed relaxed limitations. For example, Singh[7,8] reported 15 different instances of cracking in five different facilities, with SCC occurring after between 4 months and 3·5 years of service and Zuili *et al.*[9] reported five separate cases with SCC occurring after 4 months of service. Figure 12 plots these industrial failures against restrictions imposed by ISO 15156 in its original form, as modified in both 2007 and 2009, together with the further relaxations recently proposed.

Clearly there are a small number of reported industrial failures that have occurred in what is currently regarded as a 'non-susceptible' or 'safe' region by the current edition of the code. However, there are a significant number of failures which appear out with the current limitations of the code, but within the relaxation proposed based solely on laboratory testing. It appears, therefore, that there is a very significant disparity between the laboratory tests and actual industry experience.

There are several reasons that such a disparity may exist. First, reported industrial failures have predominantly occurred in the vapour phase, whilst laboratory testing is conducted in the liquid phase. Although it may be argued that corrosion is likely to be worse under fully aqueous conditions, it is also true that in regions exposed to wet vapours there is potential for chloride concentration due to the effects of evaporation and condensation. In the current failure solids removed from



11 Cooler discharge temperature profile between 2007 and 2011. Bold line indicates average operating temperature, whilst tolerance bars indicate maximum and minimum operating temperature



12 Plot of industrial failures against ISO 15156 limitations (current and previous) for AISI 316L for maximum chloride content of 1000 mg L^{-1}

the inside surface of the failed pipe contained chlorides which were higher in concentration than the liquids.

Second, residual stress could play a very significant factor in the stress corrosion of austenitic stainless steels. Residual stress will vary from weld to weld, and is strongly influenced by the welding parameters and thickness of the joint.[10] Test results could vary considerably for welded test specimens, depending on factors such as material thickness and the actual welding parameters employed.

Thirdly, test exposure time could be a significant factor. When SSCC tests are used in a qualitative manner to test a material's resistance to cracking, the test environment is normally significantly more severe than the environment that the material is likely to experience in service and the test is regarded a severe and accelerated cracking test. However, this is not the case for tests used to establish 'safe' environmental envelopes for materials according to the ISO 15156 requirements. In these cases the tests replicate the actual environment being evaluated. Consequently, these tests cannot be regarded as 'accelerated' tests, and this would mean that exposure time is likely to be much more significant, particularly as stress corrosion cracking of austenitic materials is known to include a significant incubation period; a fact corroborated by the industrial experience cited in this paper.

Finally, the surface condition of the weldment, specifically the presence of heat tint on the weld and heat affected zone, could have a significant influence on corrosion.[11] Figure 5 shows that pitting corrosion is more prevalent in the HAZ. Heat tint in this area is likely to have also removed by chemical cleaning during the metallographic examination.

Heat tint consists of various oxides, with the specific type of oxide being dependent on the chemistry of the parent metal and the thermal history of the weldment (which in turn is a function of the welding parameters). Different oxide forms may have differing corrosion resistance. Although heat tint may be removed by one or a combination of measures including wire brushing, grinding, glass beading and pickling treatments, such measures are not normally performed unless the material is for use in an aggressive acid service.[12]

Conclusions

Proposed revisions to the current ISO 15156 restrictions for austenitic stainless steel types AISI 316L appear to be inappropriate in light of industrial experience. Moreover the testing requirements for approval of materials in specific environmental conditions may be inadequate for a number of reasons, including differences between vapour and liquid environments, the role of residual stress, test duration and for welded components, the surface condition.

It is recommended that any future relaxation of the current ISO 15156 restrictions takes due cognisance of industrial experience in addition to data derived from laboratory testing.

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