Failure Analysis of a Carbon Monoxide Cryogenic Storage Tank

Chenhui Tang\textsuperscript{a}, Jinsha Xu\textsuperscript{b,}\textsuperscript{*} and Facai Ren\textsuperscript{c}

Shanghai Institute of Special Equipment Inspection and Technical Research, Shanghai 200062, PR China

\textsuperscript{a}email: tangch@ssei.cn, \textsuperscript{c}email: caifaren@163.com

\textsuperscript{b,*}Corresponding author email: xujs@ssei.cn

Abstract. The failure reasons of a carbon monoxide cryogenic storage tank were analyzed by the composition, hardness and metallography analysis. The results show that the martensite phase was found in the head skirt of the inner vessel, and the hardness of head was much higher than that of the cylinder. The comprehensive analysis indicated that the fatigue cracks on head skirt leading to the leakage failure were mainly due to the decrease in fatigue properties caused by the martensite transformation during the forming process of the head.

1. Introduction

Cryogenic liquid storage tanks are widely used in air separation industry. They generally are the vacuum powder insulation structure, and are composed of inner vessel and jacket. The cryogenic medium is contained in the inner container. The reliability and stability of inner vessel are directly related to the safe operation of storage tank. Therefore, it is of significance to analyze the cause of the inner vessel leakage.

Austenitic stainless steel is often used as the material of inner vessel because of its good low temperature toughness. With the expansion of its application in cryogenic vessels, the failure of austenitic stainless steel equipment is reported much, among which the head leakage failure is the most common. Many researchers found that the leading cause were directed to the deformation-induced martensite. Das et al.[1] studied the formation and nucleation mechanisms of deformation-induced martensite through analytical transmission electron microscopy after tensile deformation of AISI 304LN stainless steel at various strain rates at room temperature. Ma et al.[2] measured the martensite phase variables of S30408 and S30403 specimen using ferrite measuring instrument during tension. The results showed that the martensite induced with the increase of tensile deformation. Many studies showed that the martensitic transformation affected the mechanical properties, corrosion resistance and stress corrosion cracking resistance of strain-strengthened austenitic stainless steels[3-5].

The inner vessel of a carbon monoxide cryogenic storage tank was cracked and failed during operation. In this paper, the cause of leakage failure was discussed based on the composition, hardness and metallography analysis of the failure parts.

2. Service history before failure

The cryogenic storage tank has been in service for 571 days. The cracks were found in the inner vessel
of the cryogenic storage tank containing 99% carbon monoxide. The space between the inner vessel and the jacket was filled with pearl sand and evacuated. During service, the pressure, gas-phase temperature and liquid level in inner vessel change periodically, as shown in Fig. 1.

3. Macroscopic morphology
Ultrasonic testing and penetrant testing results shows that six cracks were found on the top head skirt, among which three were penetrating cracks. The three penetrating cracks were cut and sampled, and the surface morphology of cracks was shown in Fig. 2. It is noting that all the three penetrating cracks appeared on the upper head skirt and near the heat-affected zone of the circumferential weld. The crack direction is along the axis of the vessel.

Fig. 3 shows the schematic diagram of the welding seam and crack. The crack location and size data were shown in Table 1.

![Figure 1. Work conditions of the storage tank](image1)

![Figure 2. Surface morphology of the three specimens: (a) specimen 1, (b) specimen 2 and (c) specimen 3](image2)

Fig. 3 shows the schematic diagram of the welding seam and crack. The crack location and size data were shown in Table 1.

![Figure 3. Schematic diagram of the welding seam and crack.](image3)
### Table 1. Crack location and size data

| Specimen No. | 1       | 2       | 3       |
|--------------|---------|---------|---------|
| Weld thickness | 16.8    | 16.98   | 18.02   |
| Inside        |         |         |         |
| Weld width (W1) | 18.35   | 20.87   | 17.15   |
| Height of weld reinforcement (H1) | 3.10    | 3.32    | 4.01    |
| Width of HAZ (E1) | 5.37    | 4.31    | 9.29    |
| Lenth of crack (L1) | 19.95   | 7.01    | 9.89    |
| Distance from crack to weld (C1) | 4.58    | 4.24    | 5.12    |
| Outside       |         |         |         |
| Weld width (W2) | 18.02   | -       | 19.19   |
| Height of weld reinforcement (H2) | 1.70    | -       | 2.01    |
| Width of HAZ (E2) | 8.38    | -       | 5.83    |
| Lenth of crack (L2) | 13.88   | -       | 7.14    |
| Distance from crack to weld (C2) | 8.38    | -       | 5.45    |

### 4. Results and discussions

#### 4.1. Chemical composition analysis

The chemical composition analysis results of the upper head skirt are shown in Table 2. It can be seen that the material of the upper head meets the compositional requirements of S30403 in relevant standard GB/T 24511-2017 <Stainless steel and heat resisting steel plate, sheet and strip for pressure equipments>.

| Sample | Test position | Microhardness (HV) | Average Hardness (HV) |
|--------|---------------|--------------------|-----------------------|
| Sample 1 | Far away from the crack | 390 387 391 | 389 |
|         | Close to the crack | 419 418 407 | 415 |
|         | Weld seam       | 226 228 227 | 227 |
|         | Heat affected zone | 343 329 322 | 331 |
| Sample 2 | Far away from the crack | 411 404 403 | 406 |
|         | Close to the crack | 404 403 403 | 403 |
|         | Weld seam       | 231 237 222 | 230 |
|         | Heat affected zone | 341 341 343 | 342 |
| Sample 3 | Upper Head | 431 434 429 | 431 |
|         | Weld seam       | 196 198 197 | 197 |
|         | Upper cylinder  | 204 248 189 | 214 |
| Lower head and lower cylinder | Lower head | 318 326 311 | 318 |
|         | Weld seam       | 201 195 198 | 198 |
|         | Lower cylinder  | 195 200 218 | 204 |
4.3. Metallographic microstructure analysis

The micromorphology of the inner vessel is shown in Fig. 4. The metallographic structure sampling of the heads and the cylinders are close to the circumferential weld between the head and the cylinder, and the sampling of the heads are on the head skirt. It can be seen that the microstructures of heads and cylinders are all composed of white austenite, gray-black striped ferrite and gray lath martensite. However, the proportions of the phases of each part are not consistent. The content of martensite and ferrite in the cylinders is less, and the main composition of the cylinders is austenite, as shown in Fig. 4(a) and 4(b). More martensite phase appears in the upper and lower heads, as revealed in Fig. 4(c) and 4(d). The gray parallel lines in Fig. 4 are slip lines in austenite. Fig. 5 shows the morphology of the cracks of specimen 1 and specimen 2. The propagation of cracks goes along grain boundaries, and the cracks are of typical fatigue cracks.

Figure 4. Micromorphology of (a) lower cylinder, (b) upper cylinder, (c) lower head and (d) upper head.

Figure 5. Morphology of the cracks of (a) specimen 1 and (b) specimen 2.
4.4. Failure Analysis
The head skirt is not the maximum stress point of the head, nor is it the weld area with a weak
structure. However, all cracks appear on the head skirt. The phenomenon may be caused by work
hardening and deformation induced martensitic transformation of the head. During the forming
process of the head, work hardening occurs after large deformation, and the head hardness increases,
especially in the head skirt. The deformation induces martensitic transformation. The transformation
from austenite to martensite is a process of volume expansion, which significantly increases the
internal stress of the material. There is a large comprehensive stress in the head skirt, and the
comprehensive stress is the superposition of internal compressive stress, machining residual stress, and
welding residual stress. Deformation-induced martensitic transformation increases the strength of the
material, but also weakens part of the plasticity and toughness, resulting in a decrease in the plastic
forming ability and the fatigue performance of the austenitic stainless steel. Due to the large
comprehensive stress and reduced plasticity in head skirt, it is prone to fatigue cracking during service
under the action of cyclic temperature and pressure.

5. Conclusion
The results of hardness test and metallographic analysis show that the cracks on the head skirt are
mainly due to the decrease in fatigue properties caused by the martensite transformation during the
forming process of the head. In order to prevent and reduce the influence of deformed martensite, the
following measures are recommended: 1) Ensure that the content of austenite stabilizing elements (Ni,
Mn) in the stainless steel plate for the head is at a low level. For equipment under fatigue conditions, it
is recommended to use S316 series stainless steel to prevent deformation-induced martensitic
transformation. 2) Solution treatment after forming or improving the forming process was used to
reduced work hardening for cold-formed austenitic stainless steel heads.

Acknowledgments
The authors are grateful for the support by Shanghai Municipal Administration for Market Regulation
Research Project (Grant No. 2021-22).

References
[1] Das, A., & Tarafder, S.. (2009) Experimental investigation on martensitic transformation and
fracture morphologies of austenitic stainless steel. Int. J. Plast., 25(11): 2222-2247.
[2] Ma, Q.K.. (2015) Stainless steel tensile deformation to martensite transformation. Petro-Chem.
Eqpt., 2: 22-26.
[3] De, A.K., Speer, J.G., Matlock, D.K., Murdock, D.C., Mataya, M.C., Comstock, R.J.. (2006)
Deformation-induced phase transformation and strain hardening in type 304 austenitic
stainless steel. Metall. Mater. Trans. A, 37(6): 1875-1886.
[4] Singh, K.K.. (2004) Strain hardening behaviour of 316L austenitic stainless steel. Mater. Sci.
Tech., 20(9): 1134-1142.
[5] Farias, F., Alvarez-Armas, I., Armas, A.F.. (2020) On the strain-induced martensitic
transformation process of the commercial AISI 304 stainless steel during cyclic loading. Int.
J. Fatigue, 140: 105809.