Analysis of Pipeline Crack Causes Based on Mechanical Performance Testing of LNG Pipeline Under Service Conditions

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Abstract. This paper presents an experimental study on the tensile properties, impact toughness, and fatigue performance of 304/304L stainless steel used in LNG receiving station pipelines. The research obtained key performance indicators, including the tensile strength, Charpy impact energy, and the number of cycles to failure under different strain amplitudes for 304/304L stainless steel in LNG service environments. Additionally, the experimental results were utilized to analyse the causes of cracking in the inlet pipeline of an LNG receiving station. The results show that compared to room temperature, the strength of 304/304L stainless steel significantly increases at ultra-low temperatures, while its toughness decreases. However, 304/304L stainless steel exhibits good fatigue performance at both room and ultra-low temperatures. Fatigue was not identified as the cause of the cracking in the LNG pipeline. The most probable cause of the cracks is the large thermal stress induced during partial flow operation, as gravity and pressure alone cannot generate the cracks.

Keywords: LNG pipeline; crack; service conditions

1 Introduction

Large LNG storage tanks are critical infrastructure for natural gas resource reserves, with LNG being a highly hazardous material. The maximum capacity of a single tank can reach 270,000 cubic meters, and any failure could result in severe consequences [1]. During operation, the flow conditions in the storage tank's feed pipeline are complex, with significant variations in pressure and temperature. In addition, the pipeline is subjected to the combined effects of valve loads and the weight of the pipeline itself, leading to a complex loading environment. This increases the risk of crack-induced failures in the feed pipeline [2].

The failure of pipelines is closely related to the applied loads and material properties.

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Austenitic stainless steel, known for its excellent low-temperature performance, mature manufacturing processes, and cost-effectiveness, is currently the most commonly used material for pipelines in LNG receiving stations [3-5]. Since LNG operates at temperatures below -160°C, the cryogenic environment imposes stringent requirements on the mechanical properties of pipeline materials, including strength and low-temperature toughness. Numerous theoretical and experimental studies on the mechanical properties of stainless steel at cryogenic temperatures have been conducted by experts and scholars worldwide. In terms of tensile strength, Yinan Qiu et al. [6-7] summarized the variations in the mechanical properties of austenitic stainless steel with temperature. Guilherme [8] evaluated the mechanical properties of stainless steel through stress-strain curves and analyzed the causes of strain hardening based on indicators such as strain hardening rate and instantaneous strain hardening index. Marcelo Paredes [9] conducted mechanical property tests on austenitic 316 stainless steel from different manufacturers, revealing that as the temperature decreases, the kinetics of martensitic transformation induced by typical plastic strain becomes more evident, leading to a significant increase in strength but an irreversible loss in plasticity. Regarding the low-temperature toughness of steel, Shank et al. [10], in the mid-20th century, investigated numerous brittle fracture incidents in steel structures and concluded that the main cause of failure was the notch sensitivity of steel, which varies with temperature. P. Fernández-Pisón [11] conducted mode I fracture tests on two types of austenitic stainless steel in liquid helium and liquid nitrogen, finding that as the temperature decreased, the flow stress of the material significantly increased, while plasticity markedly decreased. In the field of low-temperature fatigue of metals, Jin-Sung Lee [12] carried out fatigue performance tests on three types of cryogenic metal materials and found that the fatigue strength of all materials increased as the temperature decreased. Jong-Hyun Beak [13] studied the fatigue crack growth rate of 304 stainless steel and weld metal at temperatures around -162°C. The results showed that the fatigue crack growth rate of both base metal and weld metal decreased as the test temperature lowered, with the base metal exhibiting better crack growth resistance than the weld metal.

Although extensive research has been conducted both domestically and internationally on the low-temperature properties of stainless steel, there is limited research on the mechanical properties of 304/304L stainless steel used in LNG pipelines under actual service conditions. Furthermore, no studies have yet analysed the causes of cracking in LNG pipelines. This paper aims to investigate the mechanical properties of 304/304L stainless steel under LNG service conditions and analyze the causes of pipeline cracking based on the material test results.

2 LNG Pipeline Cracking

During pipeline inspection and maintenance at a certain LNG receiving station, four surface crack defects exceeding acceptable limits were discovered at the connection weld between the valve sleeve and the upper inlet pipeline located on the top of the LNG storage tank. One of these defects was a transverse crack parallel to the weld, while the other three were longitudinal cracks perpendicular to the weld. Penetrant testing of the weld seam and heat-affected zone on the outer surface of the defect area ruled out the possibility of surface cracks. The crack dimensions were determined using an ultrasonic shear wave scan, and the results are presented in Table 1. The nominal wall thickness of the pipeline was 12.7 mm, and after measurement, the actual thickness was found to be 13.20 mm. The defect depth in the table was converted from the defect height reported in the non-destructive testing report.

Table 1. Defect information of inlet pipeline.

Defect number	Defect Name	defect information (mm)			notes
		length	buried depth	Calculate depth based on wall thickness of 13.2	
fl1	longitudinal defect 1	5	9.8	3.4	Internal surface cracks
fl2	longitudinal defect 2	10	9.2	4.0	Internal surface cracks
fl3	longitudinal defect 3	19	9.0	4.2	Internal surface cracks
fc1	Circumferential defect 1	15	10.7	2.5	Internal surface cracks

3 Material Performance Testing Under Service Conditions

Temperature significantly influences the mechanical properties of metal materials. Since LNG operates at temperatures below -160°C, the ultra-low temperature of the liquid flowing within the pipeline inevitably affects the material properties of the pipeline. Among the risks of LNG pipeline failure, the low-temperature performance of the pipe material is a critical indicator. To investigate the causes of cracking, mechanical property tests were conducted on 304/304L stainless steel used in LNG pipelines under service conditions.

3.1 Experimental Materials

The experimental material used in this study is 304/304L stainless steel piping from an LNG receiving station. The pipeline has a diameter of 660 mm and a wall thickness of 14 mm. The chemical composition of the material is presented in Table 2.

Table 2. Chemical composition of 304/304L stainless steel.

material	C	Mn	Si	P	S	Cr	Ni	N
304/304L stainless steel	0.03	2	0.75	0.045	0.03	18.0~20.0	8.0~12.0	0.1

3.2 Tensile Properties

As shown in Figure 1, flat specimens were selected and designed and processed according to GB/T 228.3-2019 "Metallic Materials – Tensile Testing – Part 3: Methods of Testing at Low Temperatures." Considering the presence of both circumferential and axial cracks in the on-site pipeline, the tensile properties in both directions—circumferential and axial—were measured in this experiment. The testing temperatures were chosen based on the actual service conditions of the LNG pipeline, specifically: the pipeline inlet temperature of -160°C, the pipeline insulation temperature of -90°C, and the ambient temperature of 20°C.

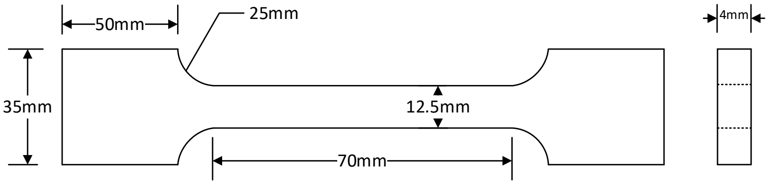

Fig. 1. Tensile specimen size.

The tensile test was conducted using a CTS-E300 microcomputer-controlled electronic universal testing machine. Prior to testing, the specimens were cooled to the corresponding test temperature using a low-temperature environmental chamber and maintained at this temperature for more than 10 minutes before the tensile test was performed. The environmental temperature was monitored in real-time during the test, and the temperature deviation before and after the test did not exceed 3°C.

All results from the tests are summarized in Table 3. Based on the test results, the sampling direction of the specimens had no effect on the tensile properties of the material, and the deviations in strength testing were within the experimental error range. When the temperature was reduced from 20°C to -160°C, the yield strength increased from 228 MPa to 454 MPa, a 99.1% increase, while the tensile strength increased from 681 MPa to 1463 MPa, a 114.83% increase. In terms of both the absolute and relative increase in strength, the tensile strength was more significantly influenced by temperature than the yield strength.

Table 3. Strength of 304/304L stainless steel at different temperatures.

temperature (°C)	Material direction	σ_y (MPa)	σ_t(MPa)
20	axial	230	683
	hoop	227	679
-90	axial	428	1195
	hoop	425	1185
-160	axial	458	1452
	hoop	450	1474

Figure 2 shows the engineering stress-strain curves of the material at different temperatures. The stress-strain curve of 304/304L stainless steel at room temperature does not exhibit a distinct yield plateau. Compared to room temperature, the stress-strain curve at low temperatures shows a significant nonlinear strain hardening phase, with the curve displaying an "S" shape.

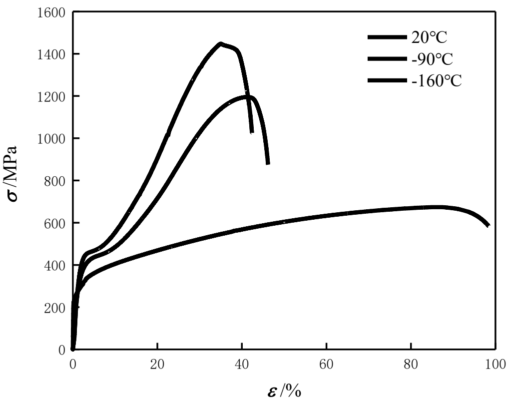

Fig. 2. Stress strain curves of 304/304L stainless steel at different temperatures.

3.3 Impact Toughness

As shown in Figure 3, Charpy impact specimens were designed and processed according to GB/T 229-2020, "Metallic Materials—Charpy Pendulum Impact Test Method." The impact toughness of the material was measured in both the circumferential and axial directions of the pipeline at temperatures of 20°C and -196°C. The tests were performed using a ZBC2452-C pendulum impact testing machine. The room temperature impact tests were conducted at 20°C. For the ultra-low temperature tests, the specimens were cooled using liquid nitrogen and should remain in the liquid nitrogen for at least 5 minutes before being transferred to the impact position. The time between removing the specimen from the liquid nitrogen and fracturing it should not exceed 5 seconds, ensuring that the specimen remains at the desired low temperature during testing.

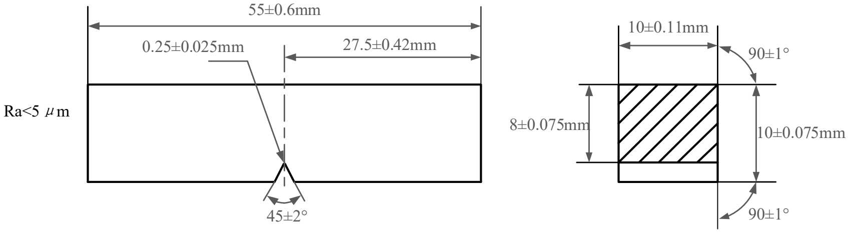

Fig. 3. Size of Charpy impact test specimen.

The test results in Table 4 show that temperature has a significant impact on the material's impact energy. From room temperature (20°C) to ultra-low temperature (-

196°C), the material's impact energy decreased by 40%, indicating that at ultra-low temperatures, the toughness of 304/304L stainless steel is significantly reduced compared to room temperature.

Table 4. Charpy impact energy of 304/304L stainless steel at different temperatures.

temperature (°C)	Material direction	Average(J)
20	axial	292.60
	hoop	297.39
-160	axial	169.88
	hoop	186.71

3.4 Fatigue Properties

As shown in Figure 4, round bar specimens were selected and designed and processed according to GB/T 26077-2021 "Metallic Materials – Fatigue Testing – Axial Strain Control Method." The fatigue properties of the material in both the circumferential and axial directions were also measured. Before crack initiation, the LNG pipeline underwent approximately 60 inlet cycles, so the low-cycle fatigue properties of the material were tested at room temperature (20°C) and ultra-low temperature (-160°C). During the test, the total strain amplitude was controlled using a high-precision extensometer. A strain rate of 0.005 s^{-1} was selected, and a triangular waveform strain control mode was used. Based on the actual service conditions of the pipeline, which generally experiences a forward load, the test was designed with a tensile-tensile loading configuration, using a commonly used load ratio of R=0.1. The cycle at which the maximum load dropped by 25% during stable cycling was selected as the effective cycle count, which represents the fatigue life. Tests were conducted at strain amplitudes of 0.8%, 1.0%, 1.5%, 3.0%, and 5.0% at both room and ultra-low temperatures, with the test results shown in Table 5. According to the low-cycle fatigue test results, 304/304L stainless steel demonstrates excellent fatigue performance both at room temperature and at ultra-low temperature. Even when the strain amplitude reaches 5%, the effective low-cycle fatigue life still exceeds 100 cycles.

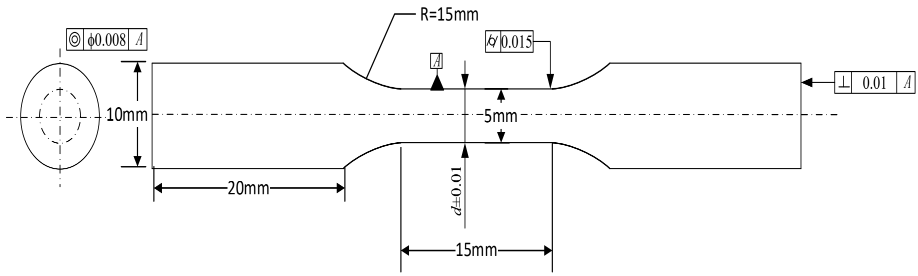

Fig. 4. Low cycle sample size.

Table 5. The number of failure cycles of 304/304L stainless steel under different temperatures and strain amplitudes.

strain amplitude	strain ratio	frequency	Number of cycles			
			-160°C		20°C	
			axial	hoop	axial	hoop
0.8%	0.1	1Hz	4193	4154	4358	4482
1.0%	0.1	1Hz	3775	3312	4005	3831
1.5%	0.1	1Hz	2093	2062	1995	2069
3.0%	0.1	1Hz	576	489	729	699
5.0%	0.1	1Hz	153	130	192	183

4 Analysis of Crack Formation in LNG Pipelines

Pipeline cracking is a result of applied loads. For LNG storage tank inlet pipelines, the loads include the weight of valves and the pipeline, temperature stresses caused by the low-temperature fluid during pipeline operation, and the internal pressure of the pipeline. The internal pressure includes the pre-commissioning pressure test and the LNG liquid pressure during the inlet process.

Based on the number of load cycles, cracks can be categorized into primary cracks and fatigue cracks. Primary cracks are typically caused by sudden external or internal loads or stress concentrations. When the material is subjected to stress exceeding its yield strength or ultimate strength, plastic deformation or fracture occurs, leading to crack formation. Fatigue cracks, on the other hand, develop from small surface defects (such as micro-voids or micro-cracks) under alternating or cyclic stresses. These defects gradually propagate, ultimately forming visible cracks.

4.1 Fatigue

For the LNG storage tank inlet pipeline described above, from the initial pre-cooling and commissioning to the detection of cracks, the total number of inlet cycles for the pipeline was approximately 60. During this period, the pipeline underwent repeated cooling cycles and inlet processes, experiencing cyclic temperature loads and internal pressure loads from the inlet process. According to the low-cycle fatigue test results of 304/304L stainless steel in its service environment, even with a strain amplitude of 5%, the number of load cycles still exceeded 100. Furthermore, during the pipeline's operation, a 5% strain would not occur. Therefore, it can be ruled out that the cracks in the inlet pipeline were caused by fatigue.

4.2 Internal Pressure of Pipeline

For the inlet pipeline described above, the internal pressure is divided into the pressure during the pre-commissioning hydrostatic test and the pressure of the LNG liquid during the inlet process. During the pressure test, the pipeline pressure is 1.5 times the design pressure, which is 2.625 MPa. During the inlet operation, the pressure in the tank top inlet pipeline is less than 0.16 MPa. A numerical simulation was conducted for the pressure test conditions of the inlet pipeline, and the results showed that the stress at the crack location of the inlet pipeline was only 60 MPa, much lower than the measured yield strength of 304/304L stainless steel at room temperature, which is 230 MPa, and therefore cannot cause pipeline cracking. Furthermore, the internal pressure-induced circumferential stress is evenly distributed along the circumferential direction of the pipeline, which cannot explain the phenomenon of crack concentration at the bottom of the pipeline.

4.3 Gravity

Field investigations revealed that there is no vertical support beneath the valve of the tank top inlet pipeline. The total weight of the valve and actuator is approximately 6.2 tons. The significant gravitational force acting on the pipeline can generate some bending stress. However, according to the principles of material mechanics, when the pipeline bends under the influence of gravity, the maximum tensile stress occurs at the outer surface of the pipeline's bottom. In contrast, the crack initiation location is on the inner surface of the pipeline. Therefore, gravity is not the cause of the pipeline cracking.

4.4 Temperature

LNG has a temperature below -160°C and is classified as an ultra-low temperature liquid. Under operating conditions such as pre-cooling, insulation, and inlet processes, the pipeline experiences significant thermal stresses. According to field monitoring data, it was observed that the pipeline exhibited severe flow maldistribution during the process operation. Furthermore, since the pipeline's insulation temperature is higher than the LNG liquid temperature, there is an uneven temperature distribution across the wall thickness and circumferential direction of the pipeline. Under the effect of a large temperature difference, due to the self-limiting nature of thermal stresses, axial and circumferential stresses at the inner surface of the pipeline bottom may have exceeded the yield strength of 304/304L stainless steel at -160°C. This is the most likely cause of pipeline crack formation, and further fluid-structure interaction (FSI) calculations are needed for verification.

5 Conclusion

1. Material mechanical property tests were conducted on the LNG receiving station pipeline under its service environment. At -160°C, the strength of the pipeline significantly increased, while its toughness decreased.

2. 304/304L stainless steel exhibits good low-cycle fatigue performance at both room temperature and low temperatures. With a strain amplitude of 5%, the number of fatigue cycles exceeds 100, indicating that fatigue is not the cause of crack formation

in the LNG receiving station inlet pipeline.

3. The loads on the inlet pipeline were analyzed. Internal pressure and gravity are not the causes of crack formation. The self-limiting nature of thermal stresses is the most likely cause of crack initiation, which requires further computational verification.

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