Article

Effect of Cryogenic Temperature on Low-Cycle Fatigue Behavior of AISI 304L Welded Joint

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Abstract: The aim of this study is to investigate the low-cycle fatigue (LCF) properties of an AISI 304L welded joint based on experimental data. The influential parameters on the LCF such as the specimen thickness, strain ratio and cryogenic temperature were considered in this experimental study. In order to investigate the thickness effect on the LCF behavior, two types of specimens with thicknesses of 5 mm and 10 mm were used in an LCF test. In addition, the fatigue tests were conducted under strain control with three different strain ratios of $R = -1$, 0, and 0.5 at room and cryogenic temperatures. Based on the results obtained by this experimental study, no significant effect involved with the thickness and the strain ratio were observed. However, it was clearly observed that LCF performance at room temperature is lower than that at cryogenic temperature. Finally, an LCF design curve that can be used in design of the liquefied natural gas (LNG) applications is suggested.

Keywords: low-cycle fatigue; welded joint; strain ratio; thickness effect; cryogenic temperature

1. Introduction

Austenitic stainless steel is one of most important structural materials used in various engineering fields owing to its excellent strength, toughness, and sufficient corrosion resistance [1,2]. Among austenitic stainless steels, AISI 304L is commonly employed to manufacture liquefied natural gas (LNG) cargo tanks because of its higher performance in a cryogenic environment. In addition, this material exhibits a special characteristic called secondary hardening owing to stress- or strain-induced phase transformation [3,4]. This state, called the martensitic transformation, leads to hardening behavior during low-cycle fatigue. It is noted that the martensitic transformation depends on the amount of plastic deformation amplitude [5].

During operation of LNG carriers, a cyclic fatigue wave caused by thermal and sloshing loads is applied in LNG cargo tanks [6]. In particular, the cryogenic temperature that is required to liquefy the natural gas affects the mechanical properties as well as the fatigue strength of LNG carriers. These parameters have a decisive influence on the low-cycle fatigue (LCF) property of the welded joints in an LNG cargo tank. In this respect, experimental studies for investigating the fatigue characteristics in the whole cycles, such as low- and high-cycles, are required to predict the fatigue life of LNG carriers.

The fatigue performance of welded joints is affected by the weld geometry, loading conditions, and material properties [7]. In general, the fatigue life of welded joints is evaluated using the stress-based approach when a fatigue fracture occurs in a high-cycle region ($N_f > 10^4$). There are three different approaches (nominal stress, structural hot spot stress, and notch stress approaches) for assessing the fatigue performance in high-cycle region. The nominal stress approach does not consider weld geometry or notch effects while the structural hot spot stress approach and the notch stress approach take into account the geometrical discontinuities in welded structures [7,8]. In particular,

the notch stress approach is effective for assessing the fatigue strength at the weld toe as well as the weld root, which are not accessible by the nominal stress approach or structural stress approach [9]. These approaches are effective and easy to apply for various fatigue design applications, but care should be exercised when they are used for low-cycle cases because they cannot consider the cyclic stress–strain behavior when localized yielding occurs owing to stress concentration [7,10]. Therefore, the strain-based approach is more suitable to predict the remaining fatigue life in low-cycle region. It is considered a plastic deformation in welded structures caused by increased local stress and strain. Local stress and strain can be calculated using an empirical formula called Neuber's rule and the Ramberg–Osgood relationship [11].

The LCF behavior of the structural steels is affected by various parameters such as the strain range, strain ratio, strain rate, and temperature. There are some research studies related to the LCF performance of structural steels, and investigations of the effect of the parameters on the fatigue strength. Vogt et al. performed an LCF test and a fatigue crack growth rate (FCGR) test for austenitic stainless steel 316L at cryogenic temperature [12]. It was clearly seen that the fatigue strength at cryogenic temperature is improved compared to that at ambient temperature. Tateishi et al. investigated the extremely low-cycle fatigue performance of a fillet-welded joint [13]. In particular, they showed that the fatigue performance in extremely low-cycle region can be improved using tungsten inert gas (TIG) dressing and burr grinding. The LCF life of a butt-welded joint was evaluated using an experimental investigation method by Benoit et al. [14]. They investigated the grain size for the base plate as well as the welded zone and strain gradient in a specimen using digital image correlation. However, most research studies related to LCF behavior have not considered the effect of the strain ratio, thickness, and cryogenic temperature on the fatigue characteristics of the welded joint.

Many LNG applications have a possibility of fatal accidents when fatigue cracks are initiated in an LNG storage tank. To accurately predict the fatigue life of LNG applications, it is required to investigate the cyclic behavior and fatigue property for an AISI 304L welded joint. Therefore, this comprehensive study shows an experimental investigation that aims at improving the low-cycle fatigue design for welded structures in cryogenic applications. In addition, this research examines the effect of thickness, stress ratio, and cryogenic temperature under strain control. Finally, a low-cycle fatigue design curve used in the design of LNG applications is suggested based on the experimental results.

2. Strain-Based Approach

It is well known that the strain-based approach can better characterize the fatigue behavior in the low-cycle region of a material than the stress-based approach [15,16]. The first procedure in the strain-based approach is to obtain the cyclic stress–strain curve of the specified material. As shown in Figure 1, the cyclic stress–strain curve is determined by connecting the maximum points of the stable hysteresis loops obtained by the results at different strain amplitudes. The cyclic stress–strain curve can be represented using the Ramberg–Osgood relationship as follows:

$$\varepsilon_a = \varepsilon_a^e + \varepsilon_a^p = \frac{\sigma_a}{E} + \left(\frac{\sigma_a}{K'} \right)^{1/n'} \quad (1)$$

where σ_a is the stress amplitude and E is Young's modulus. In addition, K' is the cyclic strength coefficient, and n' is the strain hardening exponent. It is well known that these parameters obtained by a linear regression in a log–log scale curve with different strain ratios are plotted as a linear curve. The Ramberg–Osgood equation can be employed to analyze the stress–strain relationship of notched members in combination with Neuber's rule [17].

As shown in Figure 2, the concentration factor, K_t , is equal to the value of the stress concentration factor (K_σ) and the strain concentration factor (K_ε) before the yielding point. After localized yielding occurs, the K_σ tends to decrease, while the K_ε increases. In this respect, a simple relationship called Neuber's rule is used to convert an elastically computed stress or strain into the local stress or strain. This relationship between the local stresses and strains is empirical, and it is convenient for a

number of applications unless the accuracy of the solution requires the use of a finite element analysis. Neuber's rule is given by

$$\sigma \varepsilon = \frac{(k_t S)^2}{E} \quad (2)$$

where σ and ε are the stress and strain at the notch, k_t is the stress concentration factor of the notch, S is the nominal stress applied to the component, and E is the elastic modulus.

Figure 1. Schematic of the cycle stress–strain curve obtained by hysteresis loop.

Figure 2. Effect of stress concentration and strain concentration after localized yielding.

In the strain-based approach, the fatigue life can be related to the applied strain amplitude. The total strain amplitude (ε_a) can be divided into two components: elastic strain (ε_a^e) and plastic strain (ε_a^p) from the stable hysteresis loop. In addition, the elastic and plastic strains obtained by the LCF test were clearly presented as straight curves. The elastic and plastic strains are represented using the Basquin and Coffin–Manson equations, respectively. These equations are utilized to characterize a relationship between the strain and fatigue life as follows:

$$\varepsilon_a = \frac{\sigma'_f}{E} (2N_f)^b + \varepsilon'_f (2N_f)^c \quad (3)$$

where σ'_f is the fatigue strength coefficient, E is Young's modulus, and N_f is the number of cycles to failure. In addition, b is the fatigue strength exponent, ε'_f is the fatigue ductility coefficient, and c is the fatigue ductility exponent [18]. These parameters are used to predict the fatigue life in low-cycle

regions. In this relationship, as seen in Figure 3, a special life $2N_t$ when the life of the elastic part is equal to that of the plastic part is called the fatigue transition life.

Figure 3. Plot of transition fatigue life.

3. Experimental Procedure

In this experimental study, a number of LCF tests were performed to evaluate the fatigue performance of an AISI 304L welded joint. The chemical compositions and the mechanical properties for AISI 304L and weld consumable E308LT are summarized in Tables 1 and 2, respectively. E308LT is a common consumable applied for cryogenic applications. The LCF tests were conducted using a servo-valve-controlled hydraulic testing machine (IMT-8803, INSTRON) (Instron, Norwood, MA, USA) with a load cell of 500 kN and a cryogenic chamber.

Table 1. Chemical compositions for AISI 304L and E308LT.

Material	Ni	C	Cr	Cu	Si	Mn	S	P	Mo
AISI 304L	8.63	0.016	18.2	0.5	0.376	1.451	0.0251	0.025	0.254
E308LT	10.1	0.034	19.2	-	0.59	1.52	0.013	0.023	-

Table 2. Mechanical properties of AISI 304L and E308LT.

Material	Yield Strength [MPa]	Tensile Strength [MPa]	Elongation [%]
AISI 304L	241	586	55
E308LT	527	590	42

In order to maintain the cryogenic environment, nitrogen gas was sprayed over a test specimen installed inside the cryogenic chamber during LCF tests. All LCF tests were controlled by strain using an axial extensometer with a gauge length of 10 mm. The cyclic loading was a triangular waveform with a frequency of 0.5 Hz. Five different strain amplitudes (0.2, 0.3, 0.4, 0.5, and 0.6%) were employed in the LCF tests. As shown in Figure 4, the test specimens were manufactured as a flat-sheet type in accordance with ASTM E606, and welded using flux-cored arc welding (FCAW) [19]. In order to consider the thickness effect, test specimens with thicknesses of 5 mm and 10 mm were prepared.

In addition, several LCF tests were performed at $-163\text{ }^{\circ}\text{C}$ considering the cryogenic environment effect. A series of LCF tests were conducted under three different strain ratios ($R = -1, 0$, and 0.5) to investigate the effect of the strain ratio. To obtain more accurate results, 15 specimens were used to illustrate a strain–life curve at room temperature (RT) and cryogenic temperature (CT), respectively. To compare fatigue characteristics according to changes in the strain ratio and the specimen thickness, five specimens were used in this experimental study. The failure life, which is used to present a

strain–life curve, was defined when the force dropped below 50%. Detailed conditions for the LCF tests are summarized in Table 3.

Figure 4. Detailed dimension of the test specimen.

Table 3. Low-cycle fatigue (LCF) test conditions.

Material	Stainless Steel 304L (AISI 304L)
Type of test specimen	Flat sheet type welded specimen
Control mode	Strain control, triangular waveform
Strain ratio ($R = \text{min. strain}/\text{max. strain}$)	$R = -1, 0$ and 0.5
Thickness of test specimen	5 mm and 10 mm
Strain amplitude	0.2%, 0.3%, 0.4%, 0.5%, and 0.6%
Strain frequency (Hz)	0.5 Hz
Test temperature	Room temperature and Cryogenic Temperature ($-163\text{ }^{\circ}\text{C}$)

Detailed size of weld bead is summarized in Table 4. The weld bead is covered in the narrow area in the test specimen. In addition, bead size at weld root is bigger than that at weld face. According to the effect of weld bead, all of the fatigue crack initiated at weld root, and propagated along heat affected zone (HAZ).

Table 4. Detailed size of weld bead.

Thickness	Weld Face		Weld Root	
	Width	Height	Width	Height
10 mm	12	0.6	6	1.2
5 mm	10	0.2	5	2.1

4. Results and Discussion

4.1. Thickness Effect

This comprehensive experimental study examined the effects of various parameters such as thickness, strain ratio, and cryogenic environment that are related to LCF behaviors of the welded joint fabricated using AISI 304L. Tables A1 and A2 in Appendix A show the summary of low-cycle fatigue test results obtained in this experimental study. As mentioned earlier, understanding of the fatigue behavior at low-cycle regions is important when designing LNG storage tanks. Figure 5 presents the maximum cyclic stress versus the number of cycle curves under a strain ratio of $R = 0$.

In general, there are three different characteristics (short hardening, slight softening, and significant secondary hardening) under the cyclic behavior of AISI 304L base metal [3,20]. It is

noted that the softening behavior of AISI 304L depends on the applied strain amplitude. However, the cyclic behavior of the welded joint is different from that of the base metal. In the case of the welded joint, it can be seen that cyclic softening during LCF tests was observed in the entire region after finishing short hardening in the early cyclic region between 1 and 10 cycles. In particular, this result showed that the cyclic behavior of the welded joint was similar to a characteristic of weldment in [20]. Figure 6 shows the strain–life curves for two different thicknesses (5 mm and 10 mm) under a strain ratio of $R = 0$. The 5 t and 10 t described in figures and table are 5 mm thickness and 10 mm thickness, respectively. In the comparative results, it was observed a small difference between strain–life curves of 5 mm and 10 mm. This result is similar to a tendency in the high-cycle region wherein the fatigue strength is increased with a reduction in the specimen thickness. However, this is an experimental observation and more test data is required to explain the thickness effect.

Figure 5. $\sigma_{\max}$ versus number of cycles under $R = 0$.

Figure 6. Strain–life curve for two different thicknesses under strain ratio $R = 0$.

4.2. Strain Ratio Effect

To investigate the strain ratio effect, LCF tests for specimens with a thickness of 10 mm were performed under three different strain ratios: $R = -1$, 0, and 0.5. In general, the cyclic stress–strain curve can be obtained by using the peak points in the stabilized hysteresis loops at various strain amplitudes. Figure 7 compares the cyclic stress–strain curves for three different strain ratios with a monotonic curve for a 10-mm-thick specimen. The results under $R = 0$ and 0.5 exhibited a little

more cyclic softening compared to the tendency of $R = -1$. However, there is no significant difference owing to the changes in the strain ratios $R = 0$ and 0.5 . In addition, a monotonic curve obtained from tensile test was located below those of the cyclic test results. This result demonstrates that the welded joint specimen also exhibits strong cyclic hardening that is similar to the behavior of the base metal. In particular, this characteristic is more significant at higher strain amplitudes. As mentioned earlier, the cyclic stress–strain curve is represented using Equation (1). Two parameters, K' and n' , calculated by using log–log linear regression, are summarized in Table 5. Figure 8 shows the mean stress versus number of cycle curves at a strain amplitude of 0.4% . It is clearly observed that the amount of mean stress is relaxed to a very low value during earlier fatigue cycle regions. It is well known that mean stress relaxation depends on the amount of plastic deformation [2]. To compare the fatigue behaviors under three different strain ratios, the strain amplitude versus the number of cycles to failure is presented in Figure 9. Based on the comparison results, no particular trend with respect to different strain ratios is observed. This implies that changes in the strain ratio do not significantly affect the fatigue performance of a welded joint in low-cycle region. Many studies also demonstrated that an increased mean stress has more influence on the fatigue characteristics than the effect of the strain ratio in low-cycle regions [3,21].

Table 5. K' and n' for three different strain ratios.

Strain Ratio	−1	0	0.5
K' (MPa)	1194	1268	1382
n'	0.227	0.246	0.262

Figure 7. Cyclic stress–strain curve based on Ramberg–Osgood equation.

Figure 8. Mean stress versus number of cycles at strain amplitude 0.4% .

Figure 9. Strain–life curves for thickness of 10 mm under three different strain ratios.

4.3. Cryogenic Temperature Effect

In order to examine the LCF behavior in a cryogenic environment, a series of fatigue tests were conducted at RT and CT, respectively. Figure 10 shows the cyclic stress–strain curves of a 10-mm-thick plate at RT and CT. Based on the cyclic stress–strain curves obtained from hysteresis behaviors, it can be seen that the cyclic yield strength at CT is significantly higher than that at RT owing to the cyclic hardening phenomenon. In addition, the results of the LCF test at RT are compared to those at CT, as shown in Figure 11. It is clearly seen that the fatigue performance at CT is significantly better than that at RT. In addition, this characteristic in the low-cycle region is similar to that in the high-cycle region. In general, it is well known that the fatigue resistance of structural steels increases at low temperature with an increase of the static strength [6,22].

Figure 10. Cyclic stress–strain curves at room and cryogenic temperatures under $R = -1$.

As expected, the fatigue performance of AISI 304L at CT was higher than that at RT. However, it is clearly seen that a transition fatigue life ($2N_t$) calculated at CT is lower than that at RT, as shown in Figure 12. The transition fatigue life is a key parameter for evaluating a dominant region such as an elastic strain region (high-cycle fatigue) or plastic strain region (low-cycle fatigue). The transition fatigue life is the intersection of the elastic and plastic strain curves, as shown in Figure 3 [23]. In this regard, a transition fatigue life is found when a material has an equal amount of cyclic strain between elastic and plastic terms. The elastic strain is more important in long lifetimes ($N > N_t$), and the plastic strain is dominated when fatigue failure occurs in a short-cycle region ($N < N_t$). These behaviors affect

the determination of the fatigue strength parameters (b and σ'_f) and the fatigue ductility parameters (c and ϵ'_f). As the cyclic strength increases owing to the effect of the cryogenic environment, it can be seen that the fatigue strength of the elastic part is dramatically increased compared to the case of the plastic part. It is well known that the transition fatigue life is sensitive to the hardness and tensile strength of materials [24]. Parameters b , σ'_f , c , and ϵ'_f are related to the Basquin and Coffen–Manson equation, and are summarized in Table 6. The fatigue transition life obtained by the LCF results for thickness of a 5 mm is 2664 cycles at RT and 1345 cycles at CT. In the 10-mm-thick case, the fatigue transition life is 1927 cycles at RT and 1232 cycles at CT, respectively.

Figure 11. Strain–life curve at cryogenic temperature.

Figure 12. Transition life in strain–life curve for 5 mm and 10 mm under strain ratio $R = 0$. (a) Transition life ($2N_t$) for 5 t at RT; (b) Transition life ($2N_t$) for 5 t at CT; (c) Transition life ($2N_t$) for 10 t at RT; (d) Transition life ($2N_t$) for 10 t at CT.

Table 6. Parameters for AISI 304L in Basquin and Coffin–Manson equation.

Thickness	Temperature	b	σ'_f/E	c	ϵ'_f
5 t	CT	−0.373	0.07	−1.585	443.8
	RT	−0.118	0.0045	−0.659	0.321
10 t	CT	−0.385	0.089	−1.748	1452
	RT	−0.116	0.002	−0.73	0.208

4.4. LCF Design Curve

As shown in Figure 13, the LCF design curve obtained from the experimental results by this study is compared to the existing LCF design curve for AISI 304 established by the American Society of Mechanical Engineers (ASME) code [25]. The design curve for an AISI 304L welded joint is determined based on a mean-minus-two standard deviation curve, which is associated with a 97.7% probability of survival, including test data at 5 t and 10 t. In the ASME code, LCF design curves for carbon steels, low-alloy steels, and austenitic stainless steels are suggested. In particular, the factors to cover the effects of variables such as experimental scatter surface finish, component size, and loading history are suggested to evaluate the fatigue life. As seen in the comparison, the LCF test results obtained by this experimental study exhibit lower fatigue performance compared to the ASME design curve. This implies that the ASME design curve did not properly reflect the fatigue characteristics of AISI 304L welded joints. This result also showed that the fatigue performance in low-cycle regions is significantly affected by stress concentration owing to weld geometry. In [26], it was demonstrated that a weld discontinuity is the most influential for early fatigue crack initiation at the weld toe. It is noted that although the ASME code does not reflect the effect of weld geometry, it gives specific curves or quantitative factors for considering operational environments such as elevated temperature, strain rate, and dissolved oxygen (DO) level.

Figure 13. LCF design curve for AISI 304L welded joint at RT and CT.

The cyclic yield strength (σ_{cy}) can be defined at a 0.2% strain offset, which corresponds to a plastic strain of 0.002 on the cyclic stress–strain curve. In this regard, the cyclic yield strain (ϵ_{cy}) also can be identified based on the cyclic stress–strain curve, as shown in Figure 14. As seen in Figure 13, test data obtained at RT and CT are scattered on the both narrow bands. In order to determine the fatigue design, mean-minus-two standard deviation (−2SD) curve with 97.7% probability of survival is considered in this study. The standard deviation relevant to normalized strain–life curve quantifies the distribution

of $\text{Log } 2N_f$ about the mean curve. Figure 15 shows the normalized strain–life curve obtained by using cyclic yield strains corresponding to RT and CT. This result shows that all of the LCF test data are consolidated into a narrow band normalized by the corresponding yield strain. This means that the minus-two standard deviation curve obtained by the normalized method can be used for the design of a welded structure in low-cycle region.

Figure 14. Definition of cyclic yield strength and strain.

Figure 15. Normalized strain–life curve using the cyclic yield strain.

5. Conclusions

The purpose of this experimental study was to evaluate the LCF performance of an AISI 304L welded joint at RT and CT. In addition, fatigue tests were carried out in order to investigate LCF behavior considering the effects of the specimen thickness and strain ratio. The conclusions obtained from this study are summarized as follows:

- In order to observe the thickness effect on the LCF performance of AISI 304L, two different specimens with thicknesses of 5 mm and 10 mm were tested in low-cycle region. Based on the LCF test results, the thickness effect is observed in fatigue behavior in the low-cycle region. In contrast to the behavior of AISI 304L base metal, the welded joint exhibited a softening behavior in the entire cycle region except for the initial cycle region.

- Experimental investigations were conducted in order to identify the LCF behaviors under three different strain ratios. All of the cyclic stress–strain curves were compared to a stress–strain curve obtained from a monotonic test. Although a little softening occurred in the case of $R = 0$ and 0.5 , this is not significantly different between various strain ratios such as $R = -1, 0$, and 0.5 . In terms of the fatigue property, a distinct tendency between the three different strain ratios is not observed. These results implied that the strain ratio does not affect the fatigue strength in low-cycle region.
- Based on the LCF test results at cryogenic temperature, it was clearly seen that the cyclic yield strength at CT was improved compared to that at RT. In addition, the fatigue strength in the low-cycle region increased as the test temperature decreased. This means that a special tendency for cyclic reinforcement occurred under cryogenic conditions. The transition fatigue life is an important parameter for determining the fatigue characteristic and the dominant region (elastic or plastic parts). Based on the test results, the increased tensile property affected by the cryogenic condition led to an increase in the fatigue strength in the low-cycle region.
- Based on the experimental results, a fatigue design curve for AISI 304L is presented and compared with the LCF design curve in the ASME code. This showed a clear tendency that fatigue design curve of AISI 304L weld is lower than that of the ASME code. In addition, this study showed that LCF test data corresponding to each temperature are consolidated into a narrow band using the cyclic yield strain. Finally, a fatigue design curve that can be used to evaluate the integrity of cryogenic applications was proposed.

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Appendix A

Table A1. Summary of low-cycle fatigue test results with $R = 0$.

Thickness	Room Temperature		Cryogenic Temperature	
	Total Strain Amp.	Number of Cycle	Total Strain Amp.	Number of Cycle
5 mm	0.2	21,726	0.2	10,284
	0.3	4910	0.3	8192
	0.4	1444	0.4	6048
	0.5	1090	0.5	3286
	0.6	654	0.6	2042
	0.2	13,614	0.2	20,580
	0.3	6948	0.3	4952
	0.4	2510	0.4	3996
	0.5	1290	0.5	2524
	0.6	1032	0.6	2698
	0.2	21,794	0.2	28,974
	0.3	2136	0.3	10,242
	0.4	1394	0.4	5328
	0.5	930	0.5	2666
	0.6	1266	0.6	2820

Table A1. Cont.

Thickness	Room Temperature		Cryogenic Temperature	
	Total Strain Amp.	Number of Cycle	Total Strain Amp.	Number of Cycle
10 mm	0.2	6424	0.2	10,284
	0.3	3568	0.3	8192
	0.4	2262	0.4	6048
	0.5	622	0.5	3286
	0.6	226	0.6	2042
	0.2	8736	0.2	20,580
	0.3	2072	0.3	4952
	0.4	1150	0.4	3996
	0.5	1076	0.5	2524
	0.6	714	0.6	2698
	0.2	12,788	0.2	28,974
	0.3	2428	0.3	10,242
	0.4	1704	0.4	5328
	0.5	668	0.5	2666
	0.6	456	0.6	2820

Table A2. Summary of low-cycle fatigue test results for two different strain ratios.

Thickness	R = 0.5		R = −1	
	Total Strain Amp.	Number of Cycle	Total Strain Amp.	Number of Cycle
10 mm	0.2	18,418	0.2	12,286
	0.3	2000	0.3	2024
	0.4	912	0.4	596
	0.5	638	0.5	708
	0.6	710	0.6	412

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