Experimental study of low-cycle fatigue of S30408 welded joints with strain strengthening

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Abstract. With the change of energy consumption structure, cryogenic liquids are increasingly widely used, such as liquefied natural gas (LNG), liquid hydrogen, liquid nitrogen, etc. Austenitic stainless steel is widely used in fabrication of cryogenic temperature pressure vessels as a kind of material with good lower temperature resistance. It is difficult to give full play to the high tensile strength and high plasticity reserve of austenitic stainless steel by using conventional design methods, which results in material waste and cost increase. The strain strengthening technology of austenitic stainless steel is the more effective method to realize the lightweight design and manufacture of cryogenic pressure vessel and reduce the cost. Fatigue damage is one of the typical failure modes of cryogenic pressure vessels. For the fatigue design of conventional pressure vessels, there are detailed standards, but there are few specific provisions for the fatigue design of strain strengthening pressure vessels. In this paper, experimental study on the low-cycle fatigue behavior of S30408 welded joints with 7% and 9% pre-tensile deformation were carried out.

1. Introduction
In order to meet the growing needs of society, large-scale, complex and extreme environment production is an inevitable trend [1]. On the basis of fully considering the safety of equipment, how to reduce the cost and energy consumption in manufacturing, transportation, installation and production has become a major problem to be solved in the industry [2]. As a kind of material with high tensile strength, good toughness and plasticity and good low temperature resistance, austenitic stainless steel is widely used in low temperature pressure vessels. Therefore, it is of great economic and social significance to realize the lightweight of austenitic stainless steel pressure vessel on the premise of meeting the requirements of process and ensuring safety, which can realize industrial optimization from manufacturing (saving material cost), transportation (reducing the weight of accessories), installation (reducing installation difficulty), production (reducing equipment proportion), etc. At present, the application of austenitic stainless steel strain strengthening technology is an effective scheme to realize the lightweight of low temperature pressure vessel.

Many scholars at home and abroad have been studied the strain strengthening technology of austenitic stainless steel. Hessling G. has shown that the strain strengthening technology can effectively save the materials in the manufacturing process of pressure vessels [3]. Brautigam M. has studied the strain strengthening pressure vessels in service, which shows that the microstructure of base metal, weld and heat affected zone can still remain stable after one year’s operation [4].

In reference [5], the fatigue design of cryogenic vessels with strain strengthening is studied, and the effect of strain strengthening on the fatigue life of materials and vessels is analyzed. In reference [6],...
the appropriate pressurization rate and control strategy of strain strengthening were obtained through the experimental analysis and numerical simulation of strain strengthening pressure vessel. In reference [7], the strain strengthening mobile tanker is studied, and the results show that the anti-fatigue failure ability is improved after strain strengthening treatment.

As a weak link in the pressure vessel, whether the mechanical properties of welded joint meet the requirements affects the safety of the whole pressure vessel to a certain extent. In this paper, the strain strengthening S30408 welded joint was studied, and the low-cycle fatigue experiments under different strain strengthening levels were carried out. The effects of temperature and strain strengthening level on low-cycle fatigue life were analyzed.

2. Material and Experimental

The 16mm austenitic stainless steel S30408 plate was used in the work, and the chemical composition of the base metal has been analyzed. The analyses results are shown in Table 1.

| Element C | Si | Mn | Cr | Ni | P | S |
|-----------|----|----|----|----|---|---|
| The standard value of S30408 | ≤0.08 | ≤0.75 | ≤2.00 | 18.00~20.00 | 8.00~12.00 | ≤0.035 | ≤0.015 |
| The measured value of S30408 | 0.06 | 0.37 | 1.10 | 18.18 | 8.07 | 0.028 | 0.002 |

Submerged arc welding (SAW) is used for butt welding, and welding is carried out according to the welding procedure that can pass the strain strengthening procedure qualification. The pre-tensile deformation test plates with 0%, 7% and 9% were fabricated at room temperature. According to the requirements of ASTM E606-12, the equal section smooth round bar is used as the low-cycle fatigue specimen. The specimen specification and processing requirements are shown in Figure 1.

![Figure 1. The specimens for low-cycle fatigue testing.](image)

The low-cycle fatigue testing is carried out on the reformed Instron 8801 electro-hydraulic servo fatigue testing machine. The strain control mode is adopted, and the cyclic form is triangular wave. The strain rate is 0.4%/s, and the strain amplitude is 0.6%. The first cycle starts from tensile, and the axial loading is symmetrical.

3. Analysis of Experiment Results

3.1. Analysis of cyclic stress response at room temperature

The cyclic behavior of the material changes obviously at the beginning of the cycle and the early stage of the fracture, which can be reflected by the change of stress during the cycle. The cyclic stress characteristics of welded joints with 7% and 9% pre-tensile deformation in low-cycle fatigue testing at room temperature are shown in Figure 2.
At the beginning of the cycle, the material firstly enters the hardening stage and hardens rapidly in the first 10 cycles, then the hardening rate slows down and reaches the saturation state after about 100 cycles. In addition, with the increase of pre-tensile value, the cycle stress level of the material to reach the saturation state also increases, but the low-cycle fatigue life (i.e. the number of cycles) decreases significantly.

![Figure 2](image2.png)

Figure 2. The cyclic stress of S30408 welded joint with different pre-tensile levels at room temperature.

3.2. Analysis of cyclic stress response at liquid nitrogen temperature (77K)

Figure 3 shows the cyclic stress characteristics of S30408 welded joint at room temperature and liquid nitrogen temperature. It can be seen from the figure that the cyclic stress characteristics of materials at room temperature are significantly different from those of liquid nitrogen temperature. The peak value of cyclic stress at liquid nitrogen temperature is more than twice that at room temperature.

At room temperature, the cyclic stress decreases after reaching the peak value, and the overall development trend shows four obvious stages: hardening, softening, cyclic stability, suddenly decreasing. At liquid nitrogen temperature, the cyclic stress basically remains unchanged after reaching the peak value, and the overall development trend shows three obvious stages: hardening, cyclic stability, suddenly decreasing.

![Figure 3](image3.png)

Figure 3. Comparison of cyclic stress of S30408 welded joint with 7% pre-tensile at room temperature and liquid nitrogen temperature
3.3. Analysis of cyclic deformation behavior

Figure 4 shows the stress-strain hysteresis curve of S30408 welded joint with 9% pre-tensile deformation at room temperature, and figure 5 shows the stress-strain hysteresis curve of S30408 welded joint with 7% pre-tensile deformation at liquid nitrogen temperature.

Under liquid nitrogen temperature, the material hardens rapidly in the first ten cycles, and the area of the hysteresis loop in the steady-state is obviously smaller than that in the initial-state, which indicates that the cycle energy of each cycle is decreasing and the damage is also decreasing before the material reaches the steady-state.
Figure 6. The hysteresis curve of the 10th cycle of S30408 with 7% pre-tensile deformation at room temperature and liquid nitrogen temperature (77K)

4. Conclusion
In this paper, the low-cycle fatigue testing of S30408 welded joints with different strain strengthening levels were carried out, and the fatigue characteristics of welded joints under liquid nitrogen temperature and room temperature were obtained. The influence mechanism of temperature on cyclic stress-strain and fatigue life is analyzed. At liquid nitrogen temperature, the cyclic stress of the S30408 welded joints with strain strengthening shows three obvious stages: cyclic hardening, saturation stability and fracture. Compared with fatigue characteristics under room temperature, the fatigue life and cyclic stress strength of the S30408 welded joints with strain strengthening under liquid nitrogen temperature are improved.

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