The Effect of Strain Hardening on Mechanical Properties of S30408 Austenitic Stainless Steel: A Fundamental Research for the Quality Evaluation of Strain Strengthened Pressure Vessel

Bo LI, Fa Cai REN, Xiao Ying TANG
Shanghai Institute of Special Equipment Inspection and Technical Research (SSEI),
Shanghai 200333, China
Email: libo@ssei.cn

Abstract. The austenitic stainless steel cryogenic pressure vessels are mostly used for the extreme pressure equipment. Strain hardening austenitic stainless steel cryogenic pressure vessels will undergo the plastic deformation during forming and strengthening process. However, the excessive plastic deformation will cause the performance of vessels can not to meet the requirements of related manufacturing and testing standards. Determining the mechanical properties corresponding to the different strain intensities is very important for the safety evaluation of strain strengthened vessels. For normal temperature strain hardening technology, the influence of strain rate on strain hardening and ductility attenuation of austenitic stainless steel cryogenic vessels under normal temperature is studied in this paper, for being used to evaluate the quality and safety performance of the austenitic stainless steel pressure vessel.

1. Introduction
The austenitic stainless steel cryogenic vessel is mostly used for the extreme pressure equipment for the storage and transportation of deep cold liquefied gases, such as Liquefied Natural Gas (LNG). At present, austenitic stainless steel cryogenic vessels have been widely used in the fields of energy, chemical industry, aerospace and other fields. The weight of the container can be reduced, the weight ratio can be reduced, and the energy consumption is reduced by using the strain strengthening technology. In recent years, austenitic stainless steel strain hardening technology has been used in the world to manufacture pressure vessels, which has become an important technical means for the lightweight of cryogenic pressure vessels [1-3]. Therefore, it is urgent for the industry to study the relevant quality inspection procedures, inspection and testing technologies and safety evaluation methods for strain hardening stainless steel cryogenic vessels [4-6]. Especially for the effect of strain hardening process on the mechanical properties of austenitic stainless steel materials and structures, we should strengthen basic research and experimental data accumulation. In this paper, the effect of strain and strain rate on strain hardening and ductility attenuation of austenitic stainless steel under normal temperature is detailed.

2. Experimental Details

2.1. Preparation of Strain Strengthened Stainless Steel Specimens
The different thickness (6mm, 8mm, 10mm) S30408 parent plates are used in the strain strengthening experiments. The S30408 austenitic stainless steel plates (UNS S30408 grade equivalent to EU standards in 1.4301; S30408 is also equivalent to ASTM standard ASTMA240 304) are prepared of standard specimens. According to the range of EN13458-2 appendix C, ASME CASE2596 and AS1210 Supp2-1999, the different pretension stress variables are selected. The strain rate is selected according to the loading path of the normal temperature strain strengthening technology container, and the strain is strengthened by pretension. The shape and size of the unidirectional tensile specimen used in the test are shown in the following diagram. Among them, the tensile direction is parallel to the rolling direction of the steel plate. The thickness of the sample is made of the actual plate thickness.

![Figure 1 The Size Diagram of S30408 Specimen Size for Strain Strengthening Treatment (Unit: mm)](image)

The strain rate of 0.5mm/min is used to strengthen the mechanical tensile strain of the specimens with different thickness. In the strain hardening process, the strain is precisely controlled and measured with the aid of an extensometer installed on the specimen of a tensile test machine. Mechanical stretching equipment and extensometer devices are shown in the following diagram. Strain strengthening of mechanical stretching is set to seven groups according the strain stretch length, that is, 4%, 6%, 8%, 10%, 12%, 14%, and 16% of the tensile part of the specimens.

![Figure 2 Mechanical Stretching Equipment and Extensometer Device for Tensile Strain Strengthening Treatment.](image)

2.2. Micro-structure Observation and Mechanical Properties Detection
Due to that the strain gauge is accurately controlled by extensometer in the pre stretching strain hardening process, for the partially strengthened specimen, the deformation of the center of the gauge center is the largest. Therefore, the small block specimen is taken for the micro-structure observation.

![Figure 3a, Fig.4a and Fig.5a. The main phase contains Austenite and Ferrite. The Ferrite content is about 2%-5% volume fraction.](image)

A standard mechanical tensile machine is used to test the mechanical tensile mechanical properties of the specimens which have been strained. Combined with the characteristics of the evolution of the tissue, this paper mainly focuses on the relationship between the stress and the mechanical properties.

3. Experimental Results and Analyses

3.1. The Influence of Different Strain Degrees on Micro-structure Evolution
For 6mm, 8mm, 10mm thickness plates of the S30408 parent material, the longitudinal sections of the rolling direction are selected for metallographic analysis, as shown in Fig.3a, Fig.4a and Fig.5a. The main phase contains Austenite and Ferrite. The Ferrite content is about 2%-5% volume fraction.

The strain degree is the key parameter to determine the yield strength of the material. The effects of the different strain levels on microstructure is shown in Fig.3, Fig.4 and Fig.5. When the strain is greater than 4%, the strain induced martensitic transformation occurs in the 30408 austenitic stainless steel, and needle like \(\alpha'\) martensite phase occurs. Ferrite particles or strips are obviously reduced, broken and further decomposed or dissolved. When the strain rate is constant (0.5mm/min), the ratio of martensitic phase increases with the increase of strain and deformation. After recrystallization, the grain size of austenite grain is further refined, and the average grain size decreases with the increase of
deformation.

The metastable austenitic stainless steel will produce martensitic transformation at higher temperature or when it is deformed at the lower temperature. The metastable austenitic stainless steel produces deformable martensitic transformation when the material is subjected to tensile or fatigue testing. The order is generally the austenite phase transformation $\gamma \rightarrow$ martensite phase $\varepsilon \rightarrow$ martensitic phase $\alpha'$, or directly by the $\gamma$ austenite transforms into martensite phase $\alpha'$. The $\gamma$ phase is face centered cubic structure (FCC), with low strength, good toughness and plasticity. The $\varepsilon$ is close packed six party structure (HCP), by the middle of the austenite phase which is transformed into martensite phase $\alpha'$. And as the strain of the process, the $\varepsilon$ gradually disappeared. The effect of strain rate on $\alpha'$ martensite transformation, the main mechanism of plastic deformation and deformation is related to the heating effect. In the normal temperature stretching process, the effect of thermal effect on deformation is negligible when the tensile velocity is slow (the strain rate of 0.5mm/min).

Figure 3 Metallographies of 6mm Thickness Specimens with Different Pre-strain Lengths (The Percent of Parent Material Specimen for Mechanical Tensile): (a) 0%; (b) 4%; (c) 6%; (d) 8%; (e) 10%; (f) 12%; (g) 14%; (h) 16%.

Figure 4 Metallographies of 8mm Thickness Specimens with Different Pre-strain Lengths (The Percent of Parent Material Specimen for Mechanical Tensile): (a) 0%; (b) 4%; (c) 6%; (d) 8%; (e) 10%; (f) 12%; (g) 14%; (h) 16%.
3.2. The Effect of Different Strain Degrees on Mechanical Tensile Properties at Normal Temperature

The mechanical tensile properties of the parent material plates at normal temperature are shown in Tab.1. Mechanical tensile mechanical properties of pre-tensile specimens with different parameters are tested at normal temperature. Each set of pretension parameters corresponds to the corresponding average of three sets of data, as shown in Tab.2. The change trend of mechanical properties are shown in Fig.7.

The typical pre-tensile breaking specimen, as shown in Fig.6, is in the middle of the pre-tensileed specimen and has a marked necking characteristic.

In contrast, under the conditions of that the deformation is less than or equal to 16%, and when the pre stretching rate is 0.5mm/min, with the increase of tension pre-strain, the mechanical tensile yield strength and tensile strength of 6mm thickness, 8mm thickness, 10mm thickness plates of austenitic stainless steel pre-tensile specimens are both increased with the increase of the deformation.

When the pre stretching rate is 0.5mm/min, with the increase of tension pre-strain, the deformation under the condition of less than 16%:

- The maximum tensile yield strength of 6mm plate thickness 30408 austenitic stainless steel pre-tensile specimens at normal temperature is up to 109%. The maximum tensile strength was up to 16%. The elongation of the maximum decrease of 34% of the original value of parent material.
- The maximum tensile yield strength of 8mm plate thickness 30408 austenitic stainless steel pre-tensile specimens at normal temperature is up to 101%. The maximum tensile strength was up to 16%. The elongation of the maximum decrease of 23% of the original value of parent material.
- The maximum tensile yield strength of 10mm plate thickness 30408 austenitic stainless steel pre-tensile specimens at normal temperature is up to 108%. The maximum tensile strength was up to 11%. The elongation of the maximum decrease of 32% of the original value of parent material.

| Table 1 The S30408 Parent Material Properties |
|-----------------------------------------------|
| Mechanical Property                          | 6mm Thickness Plates of S30408 Parent Material | 8mm Thickness Plates of S30408 Parent Material | 10mm Thickness Plates of S30408 Parent Material |
| Yield Strength/R_{p0.2} (Mpa)                | 302                                             | 288                                             | 304                                             |
| Tensile Strength/R_{m} (Mpa)                 | 732                                             | 701                                             | 736                                             |
| Tensile Elongation/A_{50mm} (%)              | 54.5                                            | 49.9                                            | 56.0                                            |
Table 2 The Mechanical Tensile Strain Strengthened S30408 Material Properties under Different Strain Degrees

| Specimen (Pre-tensile Strain Rate of 0.5mm/min) | Yield Strength $R_{p0.2}$ (Mpa) | Tensile Strength $R_m$ (Mpa) | Tensile Elongation $A_{50mm}$ (%) |
|-----------------------------------------------|----------------------------------|------------------------------|----------------------------------|
| 6mm Thickness Plate with pre-strain length of 4% | 414 | 741 | 48.5 |
| 6mm Thickness Plate with pre-strain length of 6% | 463 | 753 | 46.0 |
| 6mm Thickness Plate with pre-strain length of 8% | 498 | 773 | 43.0 |
| 6mm Thickness Plate with pre-strain length of 10% | 524 | 795 | 42.0 |
| 6mm Thickness Plate with pre-strain length of 12% | 576 | 809 | 39.5 |
| 6mm Thickness Plate with pre-strain length of 14% | 601 | 828 | 37.5 |
| 6mm Thickness Plate with pre-strain length of 16% | 632 | 848 | 36.0 |
| 8mm Thickness Plate with pre-strain length of 4% | 340 | 707 | 50.0 |
| 8mm Thickness Plate with pre-strain length of 6% | 422 | 730 | 49.5 |
| 8mm Thickness Plate with pre-strain length of 8% | 450 | 739 | 46.5 |
| 8mm Thickness Plate with pre-strain length of 10% | 474 | 749 | 44.0 |
| 8mm Thickness Plate with pre-strain length of 12% | 509 | 775 | 42.0 |
| 8mm Thickness Plate with pre-strain length of 14% | 542 | 790 | 40.5 |
| 8mm Thickness Plate with pre-strain length of 16% | 580 | 812 | 38.5 |
| 10mm Thickness Plate with pre-strain length of 4% | 460 | 779 | 50.0 |
| 10mm Thickness Plate with pre-strain length of 6% | 465 | 732 | 47.0 |
| 10mm Thickness Plate with pre-strain length of 8% | 514 | 754 | 45.5 |
| 10mm Thickness Plate with pre-strain length of 10% | 550 | 778 | 43.0 |
| 10mm Thickness Plate with pre-strain length of 12% | 572 | 786 | 41.0 |
| 10mm Thickness Plate with pre-strain length of 14% | 615 | 808 | 38.5 |
| 10mm Thickness Plate with pre-strain length of 16% | 632 | 818 | 38.0 |

Figure 6 Specimens with Different Pre-strain Lengths after Mechanical Tensile Tests: (a) 6mm Thickness Specimens; (b) 8mm Thickness Specimens; (c) 10mm Thickness Specimens.

The volume fraction of martensitic transformation induced by strain hardening of austenitic stainless steel can be roughly measured by ferromagnetic testing. It is necessary to explain that in actual operation, when the martensite content is less than 2%, the ferromagnetic tester is often unable to detect the results. As shown in Fig.7, it is found that the martensite content increases with the increase of the pre tensile strain length according to the test results of the martensite content of the specimen with a strain length greater than 6%. Therefore, it is not true that the higher the strain degree, the more conducive to the comprehensive mechanical properties.
Figure 7 The Change Trend of Mechanical Properties of Specimens with Different Pre-strain Lengths: (a) 6mm Thickness Specimens; (b) 8mm Thickness Specimens; (c) 10mm Thickness Specimens.

4. Conclusion
After strain hardening of S30408 austenitic stainless steel, the yield strength and tensile strength of the specimens increase with the increase of strain length and martensite content. The elongation decreased with the increase of strain strengthening degree. The positive contribution of strain strengthening effect to yield strength and tensile strength is mainly due to the refinement of grain and the increase of martensite content. While, the decrease of the plasticity index is directly related to the increase in the ratio of hard and brittle martensite phase. Therefore, in the manufacturing process of strain strengthened stainless steel pressure vessels, attention should be paid to the degradation of plastic indexes.

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