Study on mechanical properties at different test temperatures of SA-738 Gr.B plate in two states

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Abstract. This paper describes the study on mechanical properties at different test temperatures of SA-738 Gr.B plate in both delivery state and simulated post-welding heat treatment state. And the properties of the plate were characterized by tensile tests, Charpy impact tests and drop weight tests. We found that as temperature increasing, the strength of the SA-738 Gr.B plate decreased when temperature was below 200°C. While as temperature decreasing, the Charpy impact absorb energies decreased, that is, toughness of the plates became worse gradually. Through drop weight tests, we obtained the nil-ductility transition temperature for the plate. The tests data indicated the SA-738 Gr.B plate possessed good strength and toughness, which can meet the design requirements for the containment vessel and some other components of nuclear plant. The tests data also showed that post-welding heat treatment may influence both strength and toughness, so attention should be paid to simulated post-weld heat treatment when purchasing materials for plant construction. By optical microscope and scanning electron microscope, microscopic pictures have been obtained for the plate to help analyze the properties of this material, and the microstructure was the ensurance of the strength and toughness.

1. Introduction
Nuclear energy is one kind of economical, clean and safe energy resources. In contrast to traditional fossil power, nuclear power is safer and more economical [1]. AP1000 plant belongs to advanced III generation PWR (Pressurized Water Reactors) and possesses multiple passive safeguard systems. In nuclear plant, containment is used to control and restrict radioactive substances to diffuse out of reactor, and it is the last preventing nuclear radiation barrier. The containment of AP1000 is composed of two parts, including the reinforced concrete shield building outside and the cylindrical steel vessel inside that is also part of the passive containment cooling system. The material selected by AP1000 as containment vessel and its some attachments like equipment hatches is SA-738 Gr.B plates [2-5].

SA-738 Gr.B steel plate is carbon steel, which is allowed to be applied to containment vessel starting from ASME Boiler & Pressure Vessel Code version 2001. Due to the structural design requirements of containment vessel for nuclear power plant, SA-738 Gr.B steel plate was selected considering the strength and toughness or some other factors for structural design. However, there is not enough research on SA-738 Gr.B steel plate. In this paper, mechanical properties at different test temperatures of SA-738 Gr.B plate were studied so as to provide further information for nuclear power engineering application.
2. Material and tests
The test material was SA-738 Gr.B plate with size of 55mm×4000mm×8140mm, from the 5-meter plate production line of Baosteel Co. shown in Figure 1. After rolling, the plate was heat treated by quenching + tempering (QT), and then ultrasonic testing, surface inspection and size inspection were carried out. All these quality tests met design requirements, as well as chemical composition tests shown in Table 1.

![Double-stand high performance 5-meter wide and heavy plate rolling mill.](image)

**Figure 1.** Double-stand high performance 5-meter wide and heavy plate rolling mill.

| Element     | C   | Si  | Mn  | P   | S   | Ni  | Mo  | V   | Nb  |
|-------------|-----|-----|-----|-----|-----|-----|-----|-----|-----|
| Melting analysis | 0.088 | 0.18 | 1.47 | 0.003 | 0.0002 | 0.037 | 0.19 | 0.045 | 0.02 |
| Product analysis | 0.087 | 0.19 | 1.45 | 0.003 | 0.0003 | 0.038 | 0.19 | 0.043 | 0.02 |
| ASME requirement | ≤0.20 | 0.15-0.55 | 0.90-1.50 | ≤0.030 | ≤0.030 | ≤0.060 | ≤0.30 | ≤0.07 | ≤0.04 |

![Chemical analysis results.](image)

**Table 1.** Chemical analysis results.

In this research, as to the mechanical properties, both delivery state (QT) and simulated post-welding heat treatment (SPWHT) state specimens have carried out tensile tests, Charpy impact tests and drop weight tests. The SPWHT process was as follows: the specimens were holding heat in 600°C±5°C for 10hand above 425°C, the rate of heating and cooling was not less than 56°C or exceed 100°C in any hourly interval. All the tests were performed in strictly accordance with the requirements of nuclear power quality assurance system.

![Schematic diagram of sampling location for tensile test and impact test](image)

**Figure 2.** Schematic diagram of sampling location for tensile test and impact test (W-width, T-thickness).

The specimens were cut from the location of one quarter thickness at the center of the width of the plate and were perpendicular to the rolling direction of the plate, which is shown in Figure 2. As to tensile tests, the standard round specimen with diameter 10mm and gauge length 50mm were adopted.
The specimens for Charpy impact tests adopted the standard specimens with size $10\text{mm} \times 10\text{mm} \times 50\text{mm}$ according to GB/T 229-2007 [7], in addition, the bottom line of the sample notch is perpendicular to the surface of the steel plate. The specimens for drop weight tests adopted P3 standard specimens ($16\text{mm} \times 50\text{mm} \times 130\text{mm}$) according to GB/T 6803-2008 [8], which were cut from the surface at center of the width of the plate as same as the tensile tests, however, they were not at a quarter of the plate thickness, but retained one rolling surface of the plate.

3. Test results and analysis

3.1. Tensile tests

The tensile test temperature range was from $-80^\circ\text{C}$ to $250^\circ\text{C}$ and the test method was in accordance with GB/T 13239-2006 [9] for low temperature, GB/T 228.1-2010 for room temperature and GB/T 4334-2008 [10] for high temperature. The room temperature and low temperature tensile tests were conducted by MTS880 material testing machine, while the high temperature tensile tests were conducted by MTS810 material testing machine. The tensile test results include the strengths and elongations shown in Figure 3 and Figure 4.

![Figure 3. Yield strengths of the SA-738 Gr.B plate at different test temperatures.](image)

![Figure 4. Tensile strengths of the SA-738 Gr.B plate at different test temperatures.](image)
From -80°C to 200°C, yield strength and tensile strength obviously decreased as the test temperature rising in both QT and SPWHT states as shown in Figure 3 and Figure 4. From 200°C to 250°C, the two kinds of strengths tended to increasing slightly, which is can be considered as low temperature tempering brittleness phenomenon. In Figure 3, the yield strength data were about 100MPa higher than ASME requirements. As to the tensile strength, according to ASME B&PVC section II part D (Table U, GENERAL NOTES (b)), the requirement data have been revised to solid lines in Figure 4, and the test results were higher than the requirements. These data represent the plate had high strength and can meet the design requirements of nuclear power plants. From Figure 3 and Figure 4, more information can be known that both tensile strength and yield strength of SA-738 Gr.B plate in SPWHT state were lower compared with in QT state, so attention should be paid to SPWHT when purchasing materials for plant construction.

![Elongation](image)

**Figure 5.** Elongation of the SA-738 Gr.B plate at different test temperatures.

In addition, elongation after fracture can also be obtained from the tensile tests, which had a tendency to decrease as the temperature increased below 150°C as shown in Figure 5. In ASME, elongation at room temperature needs to be checked, in which the acceptance value is 20% and all the test data at different temperatures met it, so the plate had good ductility. However, comparing QT state and SPWHT state, the difference in elongation between them is not obvious, about 1% or less.

To sum up, according to the things mentioned above, yield strengths, tensile strengths and elongations have been tested from the tensile tests, and the curves of data changing with test temperatures were obtained, so the relationships with test temperatures were further understood. These data and their interrelations may be of great significance to engineering design for nuclear power plant.

### 3.2. Charpy Impact Tests

The Charpy impact test temperature range was from -100°C to 20°C and the test method was in accordance with GB/T 229-2007. Zwick PSW IWI 750 impact testing machine was adopted for the tests and the test results are shown in Figure 6.

Absorbed energy can be obtained from Charpy impact test, and Figure 6 shows the variations of the temperature-absorbed energy curve of SA-738 Gr.B plate in both delivery state and SPWHT state. Above -20°C, the absorbed energy was at upper shelf, and below -20°C, the absorbed energy began to gradually decreased and the ductile-brittle transition region changed very slowly. Through comparing QT state and SPWHT state, we can get the summary that SPWHT may reduce the toughness of SA-738 Gr.B plate under low temperature. In the figure, the dotted line is obtained by referring to ASME requirements and has a value of 68J. In both QT state and SPWHT state, the test temperature corresponding to less than 68J was very low, and this result was usually far lower than the requirements of nuclear power engineering design, thus representing that the steel plate possessed very good low-temperature impact toughness.
3.3. Drop Weight Tests
The drop weight test temperature range was from -35℃ to -50℃ and the test method was carried out according to GB/T 6803-2008 with energy 400J. New SANSI ZJC2602 tester was used for this test. The test results are shown in Table 2.

Table 2. The drop weight test results of the SA-738 Gr.B plate at different test temperatures.

| State  | Temperature       | Test Results | T<sub>NDT</sub> |
|--------|-------------------|--------------|-----------------|
| Delivery | -35℃, -40℃, -45℃ | ○, ○         | -50℃            |
| Delivery | -50℃              | ○, ×         |                 |
| SPWHT   | -35℃, -40℃, -45℃ | ○, ○         | -50℃            |
| SPWHT   | -50℃              | ○, ×         |                 |

*○* means specimen is not broken; *×* means specimen is broken.

From drop weight test, non-ductile transition temperature (T<sub>NDT</sub>) can be measured, which is 5℃ below the temperature at which at least two specimens show no-break performance before fracture. The specimens in both QT state and SPWHT state showed no break at -45℃, but at -50℃, one of the two specimens ruptured. So the T<sub>NDT</sub> was -50℃ according to the standard GB/T 6803-2008.

Figure 7 shows the determination of permissible lowest service metal temperature, and this curve can help to determine whether the TNDT tested from drop weight tests can meet the requirement (The determination formula is LST-TNDT≥A). The plate thickness is 55mm, which corresponds to the A value of 30℃, and LST for containment vessel in nuclear power design is usually more than 0℃, so TNDT≤30℃ is enough to meet the requirements. In this test, the TNDT was 50℃, which exceeded more than 20℃, and this means that non-ductile transition temperature of the SA-738 Gr.B plate was low and it can be further explained that the plate possessed good toughness.
Figure 7. Determination of permissible lowest service metal temperature.

4. Observation and analysis of microstructure
Microstructures have been observed by both Optical Microscope (OM) and Scanning Electron Microscope (SEM) for the SA-738 Gr.B plate studied above. The pictures show as follows.

Figure 8. OM micrographs of the SA-738 Gr.B plate in QT state (left) and SPWHT state (right).

Figure 9. SEM images of the SA-738 Gr.B plate in QT state (left) and SPWHT state (right)
From Figure 8 and Figure 9, the microstructures of the plate were tempered bainite with several ferrites, fine and homogeneous grains, many carbides precipitation distributed in the matrix for the plate. The microstructure of SA-738 Gr.B can be related to the properties above discussed. Comparing the micrographs in left and right of Figure 8 and Figure 9, the matrix was not changed but the precipitated carbides were in growth, which can lead to the reduction of strength and toughness of the plate in SPWHT state. Because of retaining the matrix and the fine precipitations in the matrix of the plate after SPWHT, it has good effects on maintaining higher strength and toughness of the plate.

5. Conclusions
To study the mechanical properties at different test temperatures of SA-738 Gr.B plate in two states, tensile tests, Charpy impact tests and drop weight tests have been accomplished.

In regard to tensile tests, yield strength, tensile strength and elongation data with test temperature change have been obtained. Below 200℃ the strengths and elongation were nearly decreased as temperature increasing, but from 200℃ to 250℃, they increased slightly that may be low temperature tempering brittleness phenomenon. Through Charpy impact tests, we established the variation curve of absorbed energy with temperature and obtained absorbed energy at upper shelf and the ductile-brittle transition region that changed slowly. Through drop weight tests, we obtained the nil-ductility transition temperature of SA-738 Gr.B plate which was -50℃ as a quite good result. Both Charpy impact tests and drop weight tests prove the SA-738 Gr.B plate possessed good toughness.

Comparing QT state and SPWHT state data of those tests mentioned above, simulated post-welding heat treatment may reduce the strength, the ductility and the low temperature toughness of the SA-738 Gr.B plate.

The microstructure was tempered bainite with several ferrites, fine and homogeneous grains, many carbide precipitations distributed in the matrix for the plate, which was the assurance of the strength and toughness for the material. Therefore SA-738 Gr.B plate was appropriate for some nuclear components such as containment vessel. In addition, the growth of the precipitated carbides leaded can reduce the strength and toughness of the plate in SPWHT state.

References
[1] Sun L S 2015 Microstructure and security analysis of steel used for nuclear power plant with heat treatment Foundry technology, 36 (2) 356-8
[2] Zeng G T 2012 Key tasks introduction of supervision activity of CV steel plates for AP1000 nuclear power equipment steel-made containment China heavy equipment 4 48-50
[3] Chen M and Tian H Z 2014 Properties and manufacture of steel plates for AP1000 containment Hot working technology 43(2) 96-98
[4] Zhuang Y, Wang B, Yao J T and Shi Y K 2012 New material used on containment vessel of third generation nuclear plant Material & heat treatment 41(18) 82-85
[5] Guo J, Shi X F and Li Y 2010 Material selection of equipment hatches on two nuclear power plants Petro-chemical equipment, 39(6) 80-84
[6] GB/T 228.1 2010 Metallic materials-tensile testing-part 1: method of test at room temperature (ISO 6892-1:2009, MOD)
[7] GB/T 229 2007 Metallic materials-charpy pendulum impact test-part 1: test method, Mod)
[8] GB/T 6803 2008 Test method for drop-weight test to determine nil-ductility transition temperature of ferritic steels
[9] GB/T 13239 2006 Metallic materials-Tensile testing at low temperature (ISO 15579:2000, MOD)
[10] GB/T 4334 2008 Metallic material-Tensile testing at elevated temperature (ISO 783:1999, MOD)