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Effect of tempering temperature on the microstructure and mechanical properties of a reactor pressure vessel steel

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HIGHLIGHTS

- The dependence of the deterioration of impact toughness on tempering temperature has been analysed.
- The instrumented Charpy V-notch impact test has been employed to study the fracture mechanism.
- The influence of M/A constituents on different fracture mechanisms based on the hinge model has been demonstrated.
- A correlation between the mechanical properties and the amount of M/A constituents has been established.

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ABSTRACT

The microstructure and mechanical properties of reactor pressure vessel (RPV) steel were investigated after tempering at different temperatures ranging from 580 to 700 °C for 5 h. With increasing tempering temperature, the impact toughness, which is qualified by Charpy V-notch total absorbed energy, initially increases from 142 to 252 J, and then decreases to 47 J, with a maximum value at 650 °C, while the ultimate tensile strength varies in exactly the opposite direction. Comparing the microstructure and fracture surfaces of different specimens, the variations in toughness and strength with the tempering temperature were generally attributed to the softening of the bainitic ferrite, the agminated Fe_3C carbides that resulted from decomposition of martensite/austenite (M/A) constituents, the precipitation of Mo_2C carbides, and the newly formed M/A constituents at the grain boundaries. Finally, the correlation between the impact toughness and the volume fraction of the M/A constituents was established, and the fracture mechanisms for the different tempering conditions are explained.

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1. Introduction

The safety and longevity of nuclear power plants are very important to human society [1]. The structural integrity of the reactor pressure vessel is vital for the safety of the entire nuclear power plant and determines the ultimate service life-span [2,3]. SA508 Gr.3 steels are key materials used for the fabrication of nuclear reactor facilities, such as reactor pressure vessels (RPV), steam generators, and compressors. In the past 40 years, the neutron irradiation embrittlement [4], ductile-brittle transition temperature [5,6], fracture toughness [7–9], and other characteristic properties [10–13] of SA508 Gr.3 steels have been extensively studied, and the results demonstrated that these steel show an excellent combination of irradiation resistance and other properties required for applications in third generation nuclear power reactors. In order to prolong the third generation's life-span to more than 60 years, the pressure vessels are bigger and heavier than before, and an integrated design is used to reduce the welding. Consequently, in-depth research is needed to elucidate the potential properties of the RPV steel. An appropriate processing should be adopted to enhance the performance of the heavy forgings, and assure the reliability of nuclear power components.

Heat treatment is the last thermal process in the manufacturing of large forgings before delivery; it determines the microstructure, and has direct influence on the performance of large forgings. However, with current heat treatment technology, it is difficult to guarantee the properties of these massive forgings that can reach 500 tons and have very large volumes; moreover, there has not been much research on the heat treatment of these forging steels because prior researchers have paid more attention to the metallurgy, foundry, and forging technology. With the improvement of

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large ingot casting and forging forming and the further quality requirements, people have begun to realize that heat treatment (particularly the holding temperature of austenization, the quenching cooling rate, and the tempering temperature and time) has a major influence on the microstructure and mechanical properties of large forgings. The holding temperature of austenization is a parameter that determines the austenite grain size, which has a relationship to the properties, as described by the Hall-Petch relation [14]. The different parts of a forging have different cooling rates during quenching because of the large volume. Although the continuous cooling transformation (CCT) diagram has been determined, and the qualitative relationship between the cooling speed and the microstructure has been identified in previous studies, the quantitative dependence of the mechanical properties on the cooling rate has not yet been determined. Tempering is the last step of the heat treatment process of the steel forging, and significantly affects the microstructure and properties of the forged steel. The ASTM standard [15] stipulates a tempering temperature lower than the subcritical temperature but no less than 635 °C for SA508 Gr.3 Cl.1 steel, and a minimum time of one-half hour per inch of a maximum section thickness. In the previous results, the mechanism that would explain the causal connection between the tempering temperature and time, on one hand, and the resulting microstructure and properties, on the other, was never adequately explained.

According to Sheng et al. [16], recovery and recrystallization took place during the tempering of RPV steel, and Mo_2C was precipitated. Moreover, de Villiers et al. [17] have researched the correlation between embrittlement and tempering temperature (T_t) in the range of 630–720 °C; their results indicated that the main cause of deterioration of the toughness during tempering is upper-nose temper embrittlement. In fact, martensite islands were found under high temperature because of austenite transformation; consequently, it is questionable whether or not this can be attributed to temper embrittlement. Haverkamp et al. [18] had also investigated the effect of the tempering temperature on the properties of a Mn–Mo–Ni low alloy steel; the results showed that the decrease in impact resistance results from over-tempering related to Mo_2C precipitation. In other literature, the following tempering conditions have been reported: 635 °C for 6 h [19] and 7 h 30 min [20], 645 °C for 7 h 30 min [20], 650 °C for 7 h [21], 660 °C for 10 h [22–24] and 12 h [25], and 670 °C for 30 min [26]. However, the rationale behind the selection of the tempering temperature has not been well explained. To date, a convincing answer regarding the influence of the tempering process on the microstructure and mechanical properties is still missing.

Table 1
Chemical composition (wt. %) of the steel that was investigated in this work.

Steel	C	Mn	Ni	Mo	Cr	Si	Cu	Al	Fe
SA508 Gr.3	0.17	1.41	0.82	0.51	0.13	0.17	0.03	0.011	Bal.

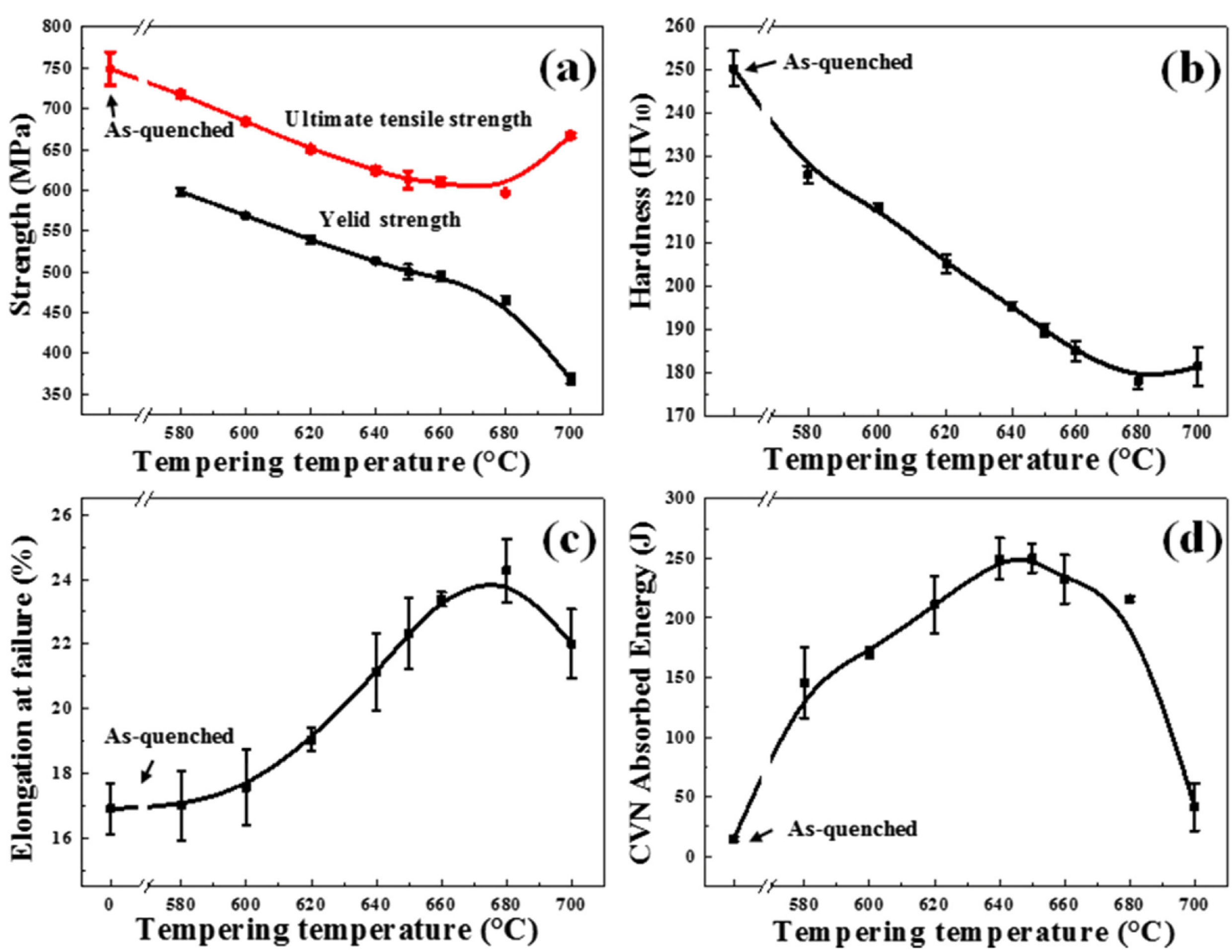

Fig. 1. Effect of tempering temperature on (a) the yield and ultimate tensile strengths, (b) hardness, (c) elongation at failure, and (d) the average value of total absorbed energy (E_t) of the Charpy V-notch impact test at −30 °C. The as-quenched state is included for comparison.

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