Steel for Nuclear Pressure Vessels

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The nuclear reactor pressure vessel is an important component of a nuclear power plant. It has been used in harsh environments such as high temperature, high pressure, neutron irradiation, thermal aging, corrosion and fatigue for a long time, which puts forward higher standards for the performance requirements for nuclear pressure vessel steel.

Keywords: nuclear reactor pressure vessels ; microstructure evolution ; mechanical properties ; irradiation ; corrosion ; thermal aging ; fatigue properties

1. Background

In recent years, the global energy crisis has swept the world. Fossil energy, such as coal, oil and natural gas, is being consumed at a visible rate, resulting in energy shortages. Currently, the world is dominated by coal power generation. However, the coal power generation not only causes environmental pollution but also leads to energy exhaustion, which will cause the global power shortage and price rise [1][2]. Nuclear energy is a kind of clean, efficient, economical and safe renewable energy [3]. Nuclear energy is one of the effective ways to solve the energy crisis. However, there has been a global anxiety about the use of nuclear power since the Fukushima accident. Therefore, research on the safety of nuclear power plants and their components is the key to the global nuclear power industry.

2. Development of Steel for Nuclear Pressure Vessels

Nuclear reactor pressure vessel (RPV) is an important component of nuclear power plant and cannot be replaced during the entire life cycle. Therefore, the steel used for RPV was generally improved on the basis of the previous generation of RPV materials. The initial material of RPV was C–Mn steel used for the boiler. The plate of SA212B, and the forgings of SA105 and SA182, were selected as the steels for first-generation RPV due to their good welding performance and high strength. However, the impact toughness and high temperature performance of C–Mn steel are poor, and the hardenability was insufficient, so the first generation of nuclear pressure vessel steel has been replaced.

The first generation RPV material was replaced by Mn–Mo-series low-alloy high-strength steel SA302B plate in order to improve the strength and toughness, which was called the second generation of RPV steel. Subsequently, the modified SA533B was made by adding 0.4–1% Ni element on the basis of SA302B, which had good strength, hardness and toughness, so it was widely used in nuclear reactor pressure vessels [4][5]. RPV materials would be damaged by strong neutron radiation during the service. However, there were more longitudinal and circumferential welds in the plates of the first and second generation RPV steels, and the position of the welds was the weak link of radiation resistance. Therefore, in order to increase the safety and reliability of nuclear pressure vessels during the service, forging materials were gradually used to decrease the welding areas. Then, the SA508Gr.2 steel was improved on the basis of SA105 and SA182 forgings by adding Ni and Ni–Mo elements. However, SA508Gr.2 steel was gradually eliminated due to insufficient hardenability, poor toughness, and reheat cracks under the surfacing layer [6].

The possibility of reheat cracks in SA508Gr.2 steel was reduced by decreasing the contents of C, Cr and Mo. Meanwhile, the Mn was added to improve the strength of RPV materials. Therefore, SA508Gr steel was improved as the third-generation nuclear reactor pressure vessel material under this background [7]. At present, SA508Gr.3 steel is the preferred material for RPVs, which decreases the area of weld joints and greatly improves the radiation resistance as well as the overall safety of nuclear power plants. Meanwhile, the widely used third-generation RPV materials also include 20MnMoNi55 steel in Germany [8][9][10], 16MnD5 steel in France [11][12], 15X2HM steel in Russia [13][14] and SA508Gr.3 steel in China [15], and so on.

With the improvement of safety performance and increase of service life of nuclear power plants, RPV materials are developing towards the direction of “large-scale integrated design” and “high safety and longevity operation”, which requires the steel used in RPV to have better hardenability and higher strength and toughness [16][17][18]. When using

SA508Gr.3 steel, it was difficult to ensure the uniformity of microstructure and the stability of properties on the extra-thick section due to the insufficient hardenability [19]. Therefore, SA508Gr.4N steel was used as the new generation nuclear pressure vessel material by increasing Ni and Cr elements and decreasing Mn element based on SA508Gr.3 steel [20]. The reduction of Mn content in SA508Gr.4N steel would decrease segregation and make the interior of the material pure, and the increase of Ni element could improve the hardenability [21]. Moreover, increasing Cr content could promote the precipitation of precipitates and refine carbides [22]. SA508Gr.4N steel was considered as candidate structural material for the new generation RPV because these had higher hardenability, better mechanical and irradiation properties compared with SA508Gr.3 steel [19][23][24][25]. The main chemical composition content of different nuclear pressure vessel materials and A508 series steel are shown in **Table 1** and **Table 2**, respectively.

Table 1. The content of main alloying elements of reactor pressure vessel steel for PWR (wt.%) [24][26].

Materials	C	Si	Mn	Cr	Ni	Mo
A212B	≤0.30	0.15–0.30	0.85–1.20	-	-	-
A302B	≤0.26	0.13–0.32	1.10–1.55	-	-	0.41–0.64
A533B	≤0.25	0.15–0.30	1.51–1.50	-	0.40–0.70	0.45–0.60
A508-2	≤0.27	0.15–0.35	0.50–0.90	0.25–0.45	0.50–0.90	0.55–0.70
US A508-3	≤0.26	0.15–0.40	1.20–1.50	≤0.25	0.40–1.00	0.45–0.55
20MnMoNi55	0.17–0.23	0.15–0.30	1.20–1.50	≤0.20	0.50–1.00	0.40–0.55
22NiMoCr37	≤0.20	0.15–0.30	1.20–1.40	≤0.40	0.40–1.00	0.40–0.55
16MND5	≤0.20	0.10–0.30	1.15–1.55	≤0.25	0.50–0.80	0.45–0.55
SFVV3	0.15–0.22	0.15–0.35	1.40–1.50	0.06–0.20	0.70–1.00	0.46–0.64
Chinese A508-3	0.19	0.19–0.27	1.20–1.43	0.06–0.12	0.73–0.79	0.48–0.51
15X2HMΦA	0.13–0.18	0.17–0.37	0.30–0.60	1.80–2.30	1.00–1.50	0.50–0.70
A508-4	≤0.23	≤0.40	0.20–0.40	1.50–2.0	2.80–3.90	0.40–0.60

Table 2. The chemical composition of A508 series steel (wt.%) [24].

Elements	Grade 1	Grade 2	Grade 3	Grade 4N	Grade 5	Grade 6
C (max)	0.35	0.27	0.25	0.23	0.23	0.28–0.33
Si (max)	0.40	0.40	0.40	0.40	0.30	0.35
Mn	0.40–1.05	0.50–1.00	1.20–1.50	0.20–0.40	0.20–0.40	0.75–1.15
Cr	≤0.25	0.25–0.45	≤0.25	1.50–2.00	1.50–2.00	0.70–1.00

Elements	Grade 1	Grade 2	Grade 3	Grade 4N	Grade 5	Grade 6
Ni	≤0.40	0.50–1.00	0.40–1.00	2.80–3.90	2.80–3.90	0.75–0.95
Mo	≤0.10	0.55–0.70	0.45–0.60	0.40–0.60	0.40–0.60	0.30–0.45

3. Service Environment of Steel for Nuclear Pressure Vessel

The safety of nuclear power plant depends on the reliability of nuclear island equipment, especially the nuclear vessel equipment that directly or indirectly contact with radioactive media, such as nuclear reactor pressure vessels, steam generators, pressurizers, etc., and the RPV also plays a role in maintaining the operating pressure balance in the reactor. RPV materials were constantly exposed to high temperature and high pressure during the service. They determined the safety and service life of nuclear power plant to a great extent [27][28][29][30]. The nuclear reactor pressure vessel contained the reactor core to prevent the leakage of radioactive substances. Therefore, the radiation damage would accompany the whole service life of RPV. **Table 3** showed the neutron fluence rate and the neutron fluence in the whole service cycle of common reactor types. It could be seen from the **Table 3** that the nuclear reactor was seriously affected by neutron irradiation during the service cycle, which would cause deterioration of the performance of nuclear pressure vessel materials.

Table 3. Neutron fluence rate and neutron fluence in common reactor (E > 1 MeV) [31].

Reactor Type	Flux, $m^{-2} \cdot s^{-1}$ (E > 1 MeV)	Lifetime * Fluence, m^{-2} (E > 1 MeV)
WWER-440 core weld	1.2×10^{15}	1.1×10^{24}
WWER-440 maximum	1.5×10^{15}	1.6×10^{24}
WWER-1000	$3–4 \times 10^{14}$	3.7×10^{23}
PWR (W)	4×10^{14}	4×10^{23}
PWR (B&W)	1.2×10^{14}	1.2×10^{23}
BWR	4×10^{13}	4×10^{22}

* Lifetime fluences for WWERs are calculated for 40 calendar years, PWRs are calculated for 32 Effective Full Power Years. However, note that this does not include the effect of service or operational life extension.

In addition, the RPV nozzle was also connected with the primary circuit main pipeline cooling system. The RPV materials were not resistant to corrosion, so a layer of austenitic stainless steel or nickel-based alloy corrosion-resistant lining would be overlaid on its inner wall to prevent corrosion. The primary cooling system was isolated from the outside world and oxygen concentration was very low, which would not cause corrosion damage to the nuclear pressure vessel system during the normal service conditions. However, the damage to the corrosion-resistant surfacing layer, stress corrosion cracking of alloy pipe penetrations at the bottom and upper closure of nuclear pressure vessels and potential leakage sources (flanges, bolts, sealing rings, valves) would lead to corrosion behavior and decrease the service life of materials during the long-term service of RPV. Therefore, corrosion was also one of the service environments of the RPV.

The service life of nuclear power plants had been increased from the original design of 40 years to 60 years with the rapid development of nuclear power technology, and it would be extended to 80 years in the future [32][33][34]. The long-term service of nuclear pressure vessel at high temperature would lead to the thermal aging behavior of the RPV materials, which would affect its microstructures and properties [35][36][37][38]. So, the service environment of RPV also included thermal aging. In addition, the RPV would be affected by fatigue damage during the service. The frequent temperature fluctuations, the start-up and shut-down process, the process of emergency shutdown and unloading would cause the RPV subjected to the influence of cyclic thermal stress, which would cause continuous fatigue damage behavior of the structural components during their lifespan [9][39][40][41]. Therefore, the fatigue damage of RPV materials was an important failure mode during the service. In summary, the service environment of RPV included high temperature, high pressure, neutron irradiation, corrosion, thermal aging and fatigue damage, as shown in **Figure 1**. During the long-term operation of nuclear pressure vessels, it not only the single service environment damaged the matrix of materials, but also the synergistic damaged of various damage mechanisms, which might cause the material to fail to meet the design standards and be scrapped in advance in the later stage of service. Herein, the effect of service environments on RPV materials are discussed one-by-one.

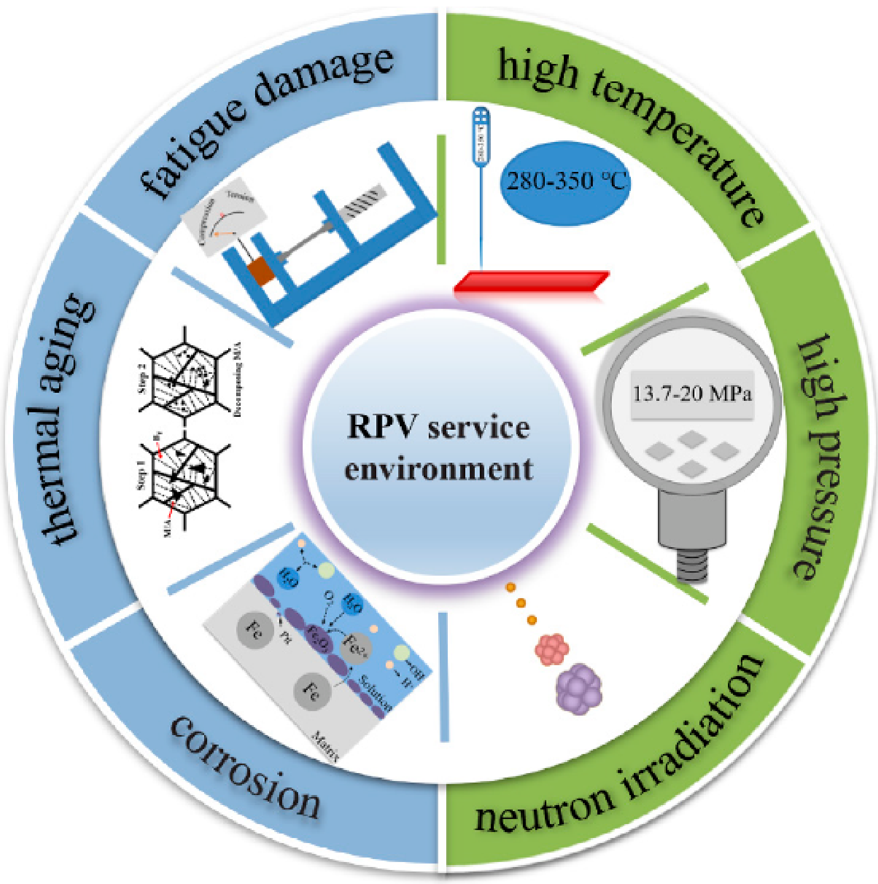

Figure 1. The service environment of nuclear pressure vessel [27][29][31][32][38][42].

4. Hot Deformation Behavior of Nuclear Pressure Vessel

RPV materials were subjected to different stages before application, such as smelting, ingot casting, forging, preheat-treatment, rough machining, quenching and tempering heat treatment, post-weld heat treatment, and delivery. Once the forging parameters were not well controlled during the forging, it was easy to cause mixed-crystal microstructures and other defects in the RPV materials, which would seriously influence the safe service performance [16][17][43]. Therefore, it was essential to study the hot deformation behavior for RPV materials.

5. Mechanical Properties of Steels for Nuclear Pressure Vessel

The ASTM standard [24] specifies that nuclear pressure vessels must meet certain mechanical properties requirements after forging, as shown in **Table 4**. Therefore, it is very important to understand the factors influencing the mechanical properties of nuclear pressure vessel materials to improve their mechanical properties. The mechanical properties of RPV materials are affected by many factors, such as alloying elements, heat treatment parameters, carbides, grain boundaries, segregation as well as hydrogen charging environment, etc.

Table 4. The mechanical properties requirements [24].

Mechanical Properties	Grades 1 and 1a	Grades 2 Class 1 and 3 Class 1	Grades 2 Class 2 and 3 Class 2	Grades 4N Class 1 and 5 Class 1	Grades 4N Class 2 and 5 Class 2	Grades 6 Class 1	Grades 6 Class 2
Tensile strength, ksi [MPa]	70–95 [485–655]	80–105 [550–725]	90–115 [620–795]	105–130 [725–895]	115–140 [795–965]	85–110 [585–760]	95–120 [655–825]
Yield strength, min [0.2% offset], ksi [MPa]	36 [250]	50 [345]	65 [450]	85 [585]	100 [690]	60 [415]	75 [515]
Elongation in 2 in. or 50 mm, min, %	20	18	16	18	16	20	18
Reduction of area, min, %	38	38	35	45	45	35	35
Minimum average value of set of three specimens, ft·lbf [J]	15 [20] (4.4 °C)	30 [41] (4.4 °C)	35 [44] (21 °C)	35 [44] (−29 °C)		20 [27] (−59 °C)	
Minimum value of one specimen, ft lbf [J]	10 [14] (4.4 °C)	25 [34] (4.4 °C)	30 [41] (21 °C)	30 [41](−29 °C)		15 [20](−59 °C)	

6. Irradiation Properties of Steels for Nuclear Pressure Vessel

The irradiation damage process of materials can be defined as the process that the incident particles transfer energy to the target, which leads to the redistribution of target atoms in the target. DPA (displacements per atom) is the number of times the atoms in a material leave the equilibrium position, and it is the basic unit of irradiation damage of a material [45][46][47]. The movement of point defects and defect clusters will occur in the process of irradiation damage [48]. The irradiation effect is the change of physical and mechanical properties caused by the movement of these defects [49]. The reactor core is wrapped inside the RPV, and its material is exposed to neutron irradiation for a long time. The microstructures will change when the nuclear pressure vessel materials are subjected to irradiation damage for a long time, such as matrix damage and impurity element segregation at grain boundaries, etc. The change of microstructures after irradiation will lead to the change of properties, such as irradiation hardness, mechanical properties and irradiation embrittlement.

7. Corrosion Properties of Steels for Nuclear Pressure Vessel

Theoretically, nuclear pressure vessel materials are rarely in direct contact with corrosive solutions due to the austenitic stainless surfacing on the inner wall of nuclear pressure vessels. However, the actual operation experience of global nuclear power plants shows that the serious corrosion behavior of RPV materials caused by the leakage of boric acid water in the primary circuit is common [27][50]. Therefore, the research on the corrosion resistance of nuclear pressure vessels needs to be given more attention in order to ensure the safe service.

8. Study on Thermal Aging of Steel for Nuclear Pressure Vessel

Thermal aging refers to a phenomenon that the microstructure of material will change under high temperature environment for a long time, and then lead to changes in the properties. Long term service of RPV materials in high temperature environment can easily cause thermal aging embrittlement. The thermal aging embrittlement of low-alloy steel is closely related to thermal aging time and temperature.

9. Fatigue Properties of Steels for Nuclear Pressure Vessel

Fatigue damage accompanied the whole service cycle of RPV, and it mainly includes two influencing factors: Material factors and environmental factors, also known as internal and external factors [51][52][53][54][55][56][57]. The essential characteristic of materials was that internal factors affected the fatigue properties, which had a decisive effect on fatigue crack initiation, cyclic hardening/softening and fatigue life. The results of some literature showed that the chemical composition, microstructures and inclusions have great influence on the fatigue properties of materials [42][52][58][59][60]. Environmental factors were the external factor that affected the fatigue properties. The influencing factor of environment on the fatigue properties of RPVs materials mainly included service environment, loading environment and natural environment, among which service environment and loading environment were common influencing factors [54][61][62][63][64][65]. Service environment included service temperature, pressure, water environment, dissolved hydrogen/oxygen and pH value, and so on. Loading environment included loading frequency, loading wave, stress ratio, stress amplitude, strain amplitude as well as the strain rate, and so on.

10. Conclusions and Outlook

Nuclear pressure vessels had been used in harsh environments such as neutron irradiation, corrosion, high temperature thermal aging and fatigue damage for a long time, which would deteriorate the properties of RPV materials. Nuclear pressure vessel materials exposed to neutron irradiation for a long time would cause matrix damage, dislocation loops and impurity element segregation, resulted in irradiation hardening and irradiation embrittlement. Although stainless steel was overlaid on the inner wall of the nuclear pressure vessel to prevent corrosion of its materials, long-term service might lead to damage of stainless steel and leakage of potential leakage sources, which would lead to directly contact between the RPV materials and boric acid corrosion solution, and then cause the occurrence of corrosion behavior. Long-term service at high temperature would cause thermal aging behavior of RPV materials, which would lead to microstructure decomposition or carbides coarsening. The thermal aging behavior mainly caused the increase of the ductile–brittle transition temperature and deteriorated the impact properties of materials. Finally, fatigue damage also accompanied the whole service process of nuclear pressure vessels. The influence factors of fatigue included microstructure evolution, second phase, service environment, corrosion environment and strain rate, etc. The fine second phase could hinder the propagation of fatigue cracks, while the coarsening second phase would become the source of crack initiation. In addition, corrosion fatigue would significantly decrease the fatigue life of materials compared with fatigue in air.

At present, the research on the nuclear pressure vessel is mostly the influence of a single factor, such as radiation, corrosion and fatigue. However, the service environment of nuclear pressure vessels is very complex, and the influence of single factor on the performance is far from the real service conditions, so the research results are insufficient and unscientific for the safety application of RPV materials. Therefore, in order to ensure their safe service in the later period of service, the collaborative mechanism of multiple service environments on nuclear pressure vessel materials should be focused on studied in future work.

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