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The action mechanism and application of alloying elements in the pressure vessel steel

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Abstract. The research progress of the influence of alloying elements on the microstructure and mechanical properties of pressure vessel steel was summarized. The effects of different alloying elements on the composite mechanical properties of the pressure vessel, such as the strength and toughness and the low temperature fracture resistance, were analysed. The action mechanism of alloying elements in pressure vessel steel was generalized. Combined with the actual production, the adding alloying elements, the research progress and the development prospect of the nuclear power pressure vessel steel were mainly analysed and discussed. The future research should focus on the mechanism of each component element, clarify the interaction relationship between the alloying elements, and develop a complete set of alloy adding scheme. So that the pressure vessel steel, which not only conforms to the actual situation, but also meet the specific requirements should be produced.

1. Introduction

In recent years, with the rapid development of the economy and society of China, energy security had become a significant strategic issue to ensure national economic security. As the statistics showed [1,2], the ratio of China's annual primary energy consumption was about 90%, of which coal was the mostly used, followed by oil. As oil consumption is high, the supply and demand gap mainly relies on imports. But the current international situation varies greatly, there is a great uncertainty risk in oil import and export trade. Therefore, the strategic oil reserve is a noticeable social hot issue nowadays. We need to use large oil storage tanks to reserve the oil. As a typical pressure vessel, the oil tank related research is carried out intensely, but most of the researches are based on the structure design and manufacture as well as production process formulation of pressure vessel product, etc. There are few systematic studies on how to improve the structure of pressure vessel steel and improve the comprehensive mechanical properties by adding different alloying elements. However, due to the effects of adding different alloying elements to improve the steel performance of pressure vessels, more and more researchers pay great attention to it. Therefore, the mechanism, application and development prospect of alloying elements in steel for pressure vessel are summarized in this paper.

2. The action mechanism of alloying elements in pressure vessel steel

All along, in order to meet the newer and higher requirements of the industrial development of pressure vessel steel, the relevant researchers are committed to the study of using different methods to improve the strength and toughness of the pressure vessel steel. But at the present stage, the most recognized method which can fundamentally solve the problem of pressure vessel steel toughness is to add a variety of different alloying elements to improve the steel structure and its comprehensive mechanical properties. The main research method is to control the types and contents of the added alloying elements to control the structure of steel and improve the comprehensive mechanical properties of steel. Because of the large variety of alloy elements, the mechanisms of various elements to improve the performance of steel are not exactly the same, after summing up, the mechanisms of action are roughly divided into four kinds. The following is a brief introduction of the alloy elements mechanism in pressure vessel steel on the basis of the recent study of scholars.

2.1. Refining grain

Adding alloying elements to refine grain is one of the most widely used mechanisms to improve steel performance. The related research shows that in the pressure vessel, the carbides formed by adding V, Nb, Ti and AlN, Al_2O_3 formed by adding Al, which are the fine particles, equivalent to inoculant, increase nucleation rate, increase the number of grains, refine the austenite grains, and then refine ferrite, so that the strength and toughness of pressure vessel steel are increased. In practical research, Wenxin Li founded that with the addition of V elements to the low alloy chromium-molybdenum pressure vessel steel, the grains were significantly refined, tensile strength ranged from 570MPa to 620MPa, the elongation ranged from 27% to 24%, the impact work ranged from 270J to 330J, the strength and toughness of materials had been significantly improved, but the plasticity dropped slightly [3]. Hui Wang used Q235 pressure vessel steels with Nb microalloyed and got the products with high strength, good ductility and low temperature impact properties [4]. In the study of grain refinement, it is of great significance to increase the content of micro-alloying elements in fine grain strengthening. Jiapeng Du studied the microstructure evolution and strengthening mechanism of Nb-Ti microalloyed steel, its microstructure is shown in figure 1 (a) and (b). It was concluded that the addition of different micro-alloying elements had significantly effect on the microstructure refinement of experimental steels [5].

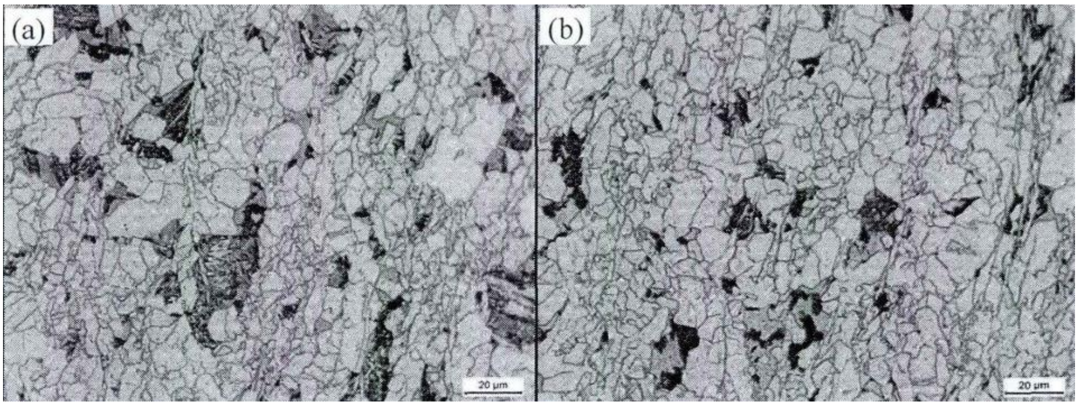

Figure 1. Microstructure of Nb-Ti microalloyed steel.

The mechanism of grain refinement is to modify the steel by adding a small amount of active materials to the steel to promote the internal nucleation of molten steel or to change the crystal growth process. Modifiers commonly used in production are tangible nuclear modifier and adsorption modifier. The mechanism of nucleation modifier is to add some substances which can produce the nonspontaneous nucleation in the melt, so as to refine the grains through heterogeneous nucleation in the solidification process. In practical research, the addition of Zr in the pressure vessel steel is a metamorphic place for sulfide, which can control the content of inclusions in steel more precisely, and improve the hardness and high temperature resistance of steel [6]. It is required that the added modifier or the reaction-generated compound has the following characteristics: the lattice structure and lattice constant are compatible with the modified melts, stability, high melting point, high dispersion in the melt, even distribution in the melt, no pollution in the alloy melt. Adsorption modifier is characterized by low melting point, can significantly reduce the temperature of the liquid phase of the alloy. Its atomic radius is large, the solution quantity in the alloy is small, so it enriches on the phase interface in the crystal growth, it blocks crystal growing up, also can form the larger supercool ingredient, causes the crystal branch to form the fine necking which is easy to fuse, promotes the crystal to be free and increases the nucleation. The disadvantage is that it often causes hot embrittlement due to the existence of grain boundaries.

2.2. Forming alloy carbide

The addition of different elements can form different alloying carbides. The types, properties and distribution of carbides in steel can directly affect the properties of steel and heat treatment phase transition. If the carbide in the steel is distributed in a diffuse form, the steel has high strength, great hardness and good abrasion resistance, which is of great significance to the use of steel. In the practical study of Ni series cryogenic pressure vessel steel, the content of P and S in the standard of 3.5% Ni steel forgings in China is higher than the standard of similar products in the United States, which has high strength, hardness and good abrasion resistance, and is the dominant steel in China [7,8]. Alloying elements can be divided into four categories according to the affinity of alloying elements and carbon, and detailed descriptions are shown in table 1.

Table 1. The affinity of alloying elements and carbon.

Affinity between alloying elements and carbon	Main Representative elements	Nature and role
Non-carbide forming elements	Ni, Co, Cu, Si, Al, B	Not forming carbide, dissolving in ferrite and austenite, forming alloy ferrite and alloy austenite.
Weakly carbide forming elements	Mn	The carbon affinity is weak, most soluble in ferrite or austenite, less partially soluble in cementite, forming alloying cementite.
Medium carbide forming elements	Cr, Mo, W	The carbon affinity is high. It can form alloy cementite, which can improve hardness and obviously improve the strength of low alloy steel. The microstructure is stable.
Strong carbide forming elements	V, Nb,Ti	It forms special carbides with carbon. It has a higher melting point, hardness and wear resistance than alloy cementite, the microstructure is more stable.

2.3. Enhancing ferrite

Most alloying elements dissolve in α-Fe and form alloying ferrite, which is caused by the distortion of lattice, resulting in the effect of solid solution strengthening, the strength of pressure vessel steel is increased, the hardness is increased, the ductility toughness is reduced. Through the references [9,10], the effect of several alloying elements on toughness is summarized as follows: If Si<1.0%, Mn<1.5%, the toughness of ferrite does not decrease, if the quantity is more than this number, the toughness of ferrite decreases, if Cr≤2% and Ni≤5%, the ferrite is obviously strengthened and the ferrite toughness is enhanced.

2.4. Improving the stability of steel

The stability improvement of the pressure vessel steel by alloying elements is mainly reflected in improving the tempering stability of steel. Adding an appropriate amount of alloying elements can make steel improve the resistance ability of softening and hardness decline when tempering, so as to improve the purity of steel and temper stability. The cause of this phenomenon is that the alloying elements hinder the decomposition of martensite, and carbide is not easy to be precipitated, even if the precipitation is not easy to grow up, it always maintains a greater degree of dispersion, resulting in decreased hardness and improved stability. In practical research, the composite alloying process of reduced carbon, improved Mn and microalloyed V and Ti is used to improve the tempering stability of steel. The purity and tempering stability of the steel is improved by using the external pulverized-coal desulfurization, controlled rolling and controlled cooling technology and proper heat treatment technology, and the formation of sulfide inclusions in steel is changed, thus the low temperature impact toughness of C-Mn steel is obviously improved [11].

3. The application and development of alloying elements in the pressure vessel steel

When the manufacturing process of the ordinary pressure vessel steel develops to a certain stage, it is found that the ordinary pressure vessels could not meet the requirements of the corresponding environment under some special environmental conditions. Therefore, as the representative of the new generation pressure vessels, a variety of special pressure vessels are unconsciously standing at the forefront of the development of pressure vessels [12]. The special pressure vessel steel is to adjust the performance of steel by adding different kinds and different content of alloying elements to ordinary steel and using their different performances in steel [13]. Common special pressure vessel steels are: the corrosion resistant pressure vessel steel, low temperature resistant pressure vessel steel and nuclear power pressure vessel steel.

Nuclear energy is one of the most important energy sources of human society in the future. Nuclear power pressure vessel is indispensable for the development of nuclear energy [14,15]. The comprehensive performance of steel for nuclear power pressure vessels is improved by adding certain alloying elements. The general trend of related research should be as follows: The matrix reinforcement method of the traditional single alloy element is gradually transformed into that with a small number of elements to strengthen and toughen the matrix. On the basis of the existing technology, the purity of the steel is further improved and the impurity segregation is reduced, and the carbide forming elements in the material are decreased or eliminated.

4. Conclusions

In this paper, the mechanism of alloying elements in pressure vessel steel was summarized, the influence of different alloying elements on the comprehensive properties of pressure vessel steel was analyzed, and the application of alloying elements in pressure vessel steels was discussed. The following conclusions were drawn:

(1) Because of the various alloying elements, the mechanisms of the elements to improve the performance of the steel are not the same, roughly divided into four kinds of mechanism, namely: refining the grain mechanism, forming the carbide alloy mechanism, strengthening the ferrite mechanism and improving the stability of steel mechanism. It is found that the complex mechanism of alloying elements is formed by the interaction of various mechanisms.

(2) The properties of steel for nuclear power pressure vessel should be improved by increasing the content of favourable elements and reducing the content of harmful impurities. At the same time, it is necessary to study the mechanism of each component element, to find out the interaction between each alloying element, and to make a complete set of alloying element adding scheme to produce the pressure vessel steel which conforms to the actual production conditions and meets the requirements of the specific conditions.

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