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Research Article

Influence of Microalloying Element on the Microstructure and Mechanical Properties of 34CrNiMo6 Steel for Wind Turbine Main Shaft

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The influence of the microalloying elements of 34CrNiMo6 steel on the microstructure and mechanical properties is investigated in this paper, especially Al and N. Then, the testing of the tensile strength, yield strength, elongation after breakage, and impact absorbing energy under the different conditions is carried out to compare the mechanical properties of materials. Based on the experimental results, the evolutions of mechanical properties with the content of aluminum are obtained. The average grain size test and scanning electron microscope results illustrate that the strengthening mechanism is the pinning effect of aluminum nitride.

1. Introduction

As one of the three major renewable energy resources, wind power is being exploited on a large scale for global power generation, alongside solar power and hydropower [1]. According to the estimation of the International Energy Agency (IEA), the annual wind-generated electricity of the world will reach 1282 TW·h by 2020. By 2030, this figure will reach 2182 TW·h [2]. Nowadays, the power of wind turbines has been increased from kilowatt-class to million-watt-class, which requires the wind turbines have the higher safety and reliability, correspondingly [3]. That is to say, the mechanical properties of material used for making main bearing must meet the demands [4]. The 34CrNiMo6 steel is one kind of heat-treated low-alloy engineering steel with high strength and hardenability, which contains nickel, chromium, and molybdenum [5]. Moreover, the 34CrNiMo6 steel also has good toughness properties at low temperature, which ensures the shock resistance of the material is good enough in the service temperature environment. In the actual process, the requirements of the materials are super strict due to the difficulty of maintenance and large economic losses. There are two main approaches to optimize the mechanical properties of material in actual industrial production [6]. One is the parameters optimization during process: optimizing the steel-making process, increasing the times of forging, and extending the forging period time. The other is regulating the composition of steel: adjusting the content of microalloying elements to optimize the microstructures of steel.

The current research was devoted to evaluate the microstructure evolution of 34CrNiMo6 steel components during heat treatment process. Džugan et al. [7] used a thermomechanical simulator during thermomechanical process to improve the fatigue life of 34CrNiMo6 steel. The variables in experiments are cooling rate from the forming temperature and annealing temperatures, which could make samples with various microstructures. The final samples could be used for highly loaded components with very high hardenability, fatigue strength, and toughness. Liu et al. [8] investigated the relationship between cutting tool life and speed to improve the cutting performance and wear mechanism of 34CrNiMo6 steel. Popescu et al. [9] studied on the parameters of bulk tempering process on the

hardenability and temperability of 34CrNiMo6 steel. The experiment investigated the correlation between the hardness achieved after high tempering on products and their equivalent diameter and the heat and time parameters of tempering. Chunping et al. [10] studied the effects of cooling condition on microstructure and mechanical properties in laser rapid forming of 34CrNiMo6 thin-wall component. The experiment used three kinds of cooling conditions, that is, water cooling, metal cooling, and air cooling to prepare 34CrNiMo6 steel thin-wall component by laser rapid forming (LRF) technology. The results showed that the cooling condition had significant effects on the microstructure and mechanical properties of 34CrNiMo6 steel due to the different tempering effects of subsequent LRFed process. Cochet et al. [11] investigated the heat treatment parameters of 34CrNiMo6 steel used for shackles. The results firstly provided a validation of the input data and the prediction of the phase volume fractions and the resulting hardness, which showed that the proposed approach could yield a very good representation of the material properties. The heat treatment method could improve the mechanical properties significantly, but raises the costs of production; hence, it is not conducive to large-scale production in industry [12]. Regulating the composition of steel to improve the mechanical property is a more reasonable choice for industrial production. However, there are very few research studies about the effect of alloy elements on the microstructure of 34CrNiMo6 steel. This paper investigates the influence of the microalloying elements of 34CrNiMo6 steel on the microstructure and mechanical properties. At the given heat treatment process conditions, adjusting the content of different alloy elements especially the ratio of aluminum to nitrogen to change the microstructure of the material. Then, testing of the tensile strength, yield strength, elongation after breakage, and impact absorbing energy under the different conditions is carried out to compare the mechanical properties of materials.

2. Materials and Methods

2.1. Composition Design. To investigate the influence of the microalloying elements on the microstructure and mechanical properties of 34CrNiMo6 steel, five different experimental parameters were carried out in this study. As shown in Table 1, the contents of Al are 0, 0.016, 0.02, 0.025, and 0.027 (wt.%), respectively, with the strict control of S and P. However, S is usually combined with manganese to form manganese sulfide, one of the common nonmetallic inclusions, which will reduce the cohesion strength because of the temper embrittlement [13]. P has the strongest influence due to grain boundary segregation [14].

2.2. Mechanics Performance Test. The mechanics performance testing contains tensile strength, yield strength, elongation after breakage, and impact absorbing energy test. Strength is one of the main mechanical properties of metals and alloys, which is defined as the amount of stress that a material can withstand while being tensile or compressed before failing. Toughness refers to the ability of a metal to resist fracture by absorbing impact energy and plastic deformation. Fracture toughness is used to characterize toughness. An impact test is used to give an indication of fracture toughness through measuring the resistance of the material to impact load without fracture [15], which can be used as a tool to evaluate the ductile-brittle transition temperature.

Table 1: Chemical composition of 34CrNiMo6 steel.

No.	C	Si	Mn	P	S	Cr	Ni	Mo	Cu	Al
1	0.35	0.25	0.77	0.012	0.002	1.59	1.54	0.25	0.07	0
2	0.36	0.22	0.76	0.006	0.002	1.56	1.55	0.23	0.06	0.016
3	0.35	0.26	0.75	0.005	0.001	1.58	1.55	0.23	0.06	0.02
4	0.35	0.22	0.73	0.011	0.001	1.57	1.54	0.22	0.08	0.025
5	0.36	0.25	0.73	0.008	0.001	1.56	1.53	0.22	0.07	0.027

The tensile test is based on the standard ASTM E8, and the specimen is taken from the 1/4 position of circular cross section of the 34CrNoMo6 diameter, whose original diameter is 10 mm, original standard distance is 50 mm, and total length is 120 mm. The tensile test was carried out via the hydraulic universal tester WAW-300B. The samples were tested 3 times, and the test results were averaged for each group of samples.

According to the standard ASTM A370-2013a, the impact tests are carried out to measure impact absorbing energy. The specimen is shaped as V-type taking from the 1/4 position of circular cross section of the 34CrNoMo6 diameter, whose total length is 50 mm. The height and width of the section both are 10 mm, the notch angle is $45 \pm 2^{\circ}$, and the height of the notch at the bottom is 8 mm. The impact tests were carried out by the impact testing machine ZBC2302. The samples were tested 3 times, and for each group of samples, the test results were averaged.

2.3. Average Grain Size Test. The grain size is one of the most important parameters of the production made by alloy steel, which can be used as criteria of the material. The paper measured the average grain size to reflect the grain size number of 34CrNiMo6 steel, based on the standard EN 10083-3. The specimens from the 34CrNiMo6 steel were suitably sectioned, mounted, mechanically polished, and etched. The etchant was a weak solution (4.0 wt.%) of nitric acid and alcohol. The specimens were observed using a TV-400D optical microscope and a ZEISS SIGMA field-emission scanning electron microscope.

3. Results and Discussion

3.1. Mechanics Performance Test Results. The evolutions of mechanical properties with the content of aluminum are shown in Figure 1, respectively.

All the mechanical properties, tensile strength, yield strength, and elongation after breakage, increase firstly and then decrease with the content of aluminum increasing. The values of tensile strength, yield strength, and elongation after breakage reach the peak at about 0.02 wt.%, which are increased by 9.3%, 12.8%, and 19.5%, respectively.

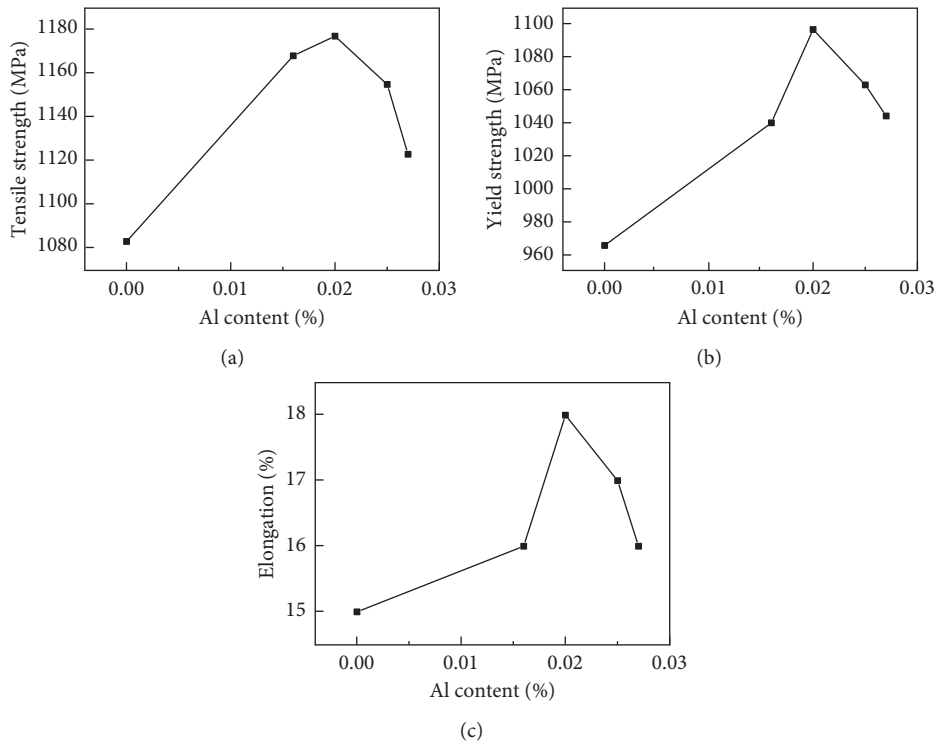

Figure 1: The evolutions of mechanical properties with the content of aluminum. (a) Tensile strength. (b) Yield strength. (c) Elongation after breakage.

Figure 2 shows the hardening curves of 34CrNiMo6 steels in tensile tests with the content of aluminum. As shown in Figure 2, no matter whether aluminum is added or not, the ductility of 34CrNoMo6 steel is very good, and the two stress-strain curves (Al = 0% and Al = 0.02%) both have clear upper yield points. Moreover, the yield strength, tensile strength, and ductility of the 34CrNiMo6 steel are all increased when 0.02 wt.% aluminum is added into the 34CrNiMo6 steel.

There are many factors affecting the strength of 34CrNiMo6 steel, some of which are related to the initial chemical composition like alloying elements [16]. Al is one kind of element which could make the material a fine grain size to increase the strength [17]. Moreover, the Al element could promote the resistance to dislocation movement to increase strength. According to the experimental results, the mechanical properties of 34CrNiMo6 steel cannot meet the requirements $Rm \geq 1100$ MPa and $Re \geq 1000$ MPa when there is no Al adding. By contrast, the tensile strength and yield strength both could meet the requirements when the content of Al is from 0.016 wt.% to 0.027 wt.%.

Like other mechanical properties, the impact absorbing energy increases firstly and then decreases with the content of aluminum increasing both at test temperature 20°C and −40°C. The values of impact absorbing energy under different temperatures reach the peak at about 0.02 wt.%, which are increased by 12.5% at 20°C and 33.3% at −40°C, respectively. Compared with the impact absorbing energy at 20°C, Al element has a greater impact on the impact absorbing energy. Similar to the previous, the impact toughness of 34CrNiMo6 steel can be improved with refinement of the prior austenite grain size.

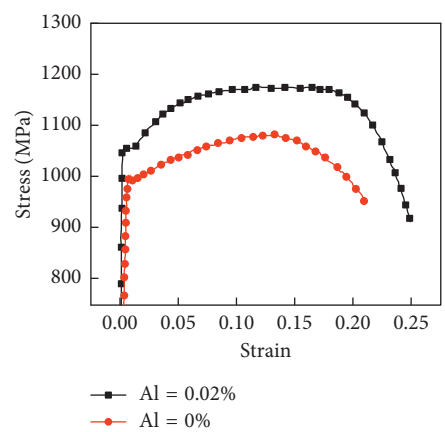

Figure 2: Hardening curves in tensile tests with the content of aluminum.

3.2. Average Grain Size Test Results. According to the corresponding literatures [18], the smaller the average grain size is, the better the mechanical properties the material have. According to the aluminum-nitride-controlling grain boundary migration theory, it could define the average grain size by adjusting contents of aluminum and nitride. The contents of H, O, and N in 34CrNiMo6 steel are shown in Table 2. The content of N is basically the same order of

Table 2: The contents of H, O, and N in 34CrNiMo6 steel.

No.	H (ppm)	O (ppm)	N (ppm)	Al (wt.%)	Al/N
1	1.5	18	67	0	—
2	1.6	19	70	0.016	2.2
3	1.5	20	69	0.02	2.8
4	1.5	20	70	0.025	3.6
5	1.7	19	66	0.027	4.1

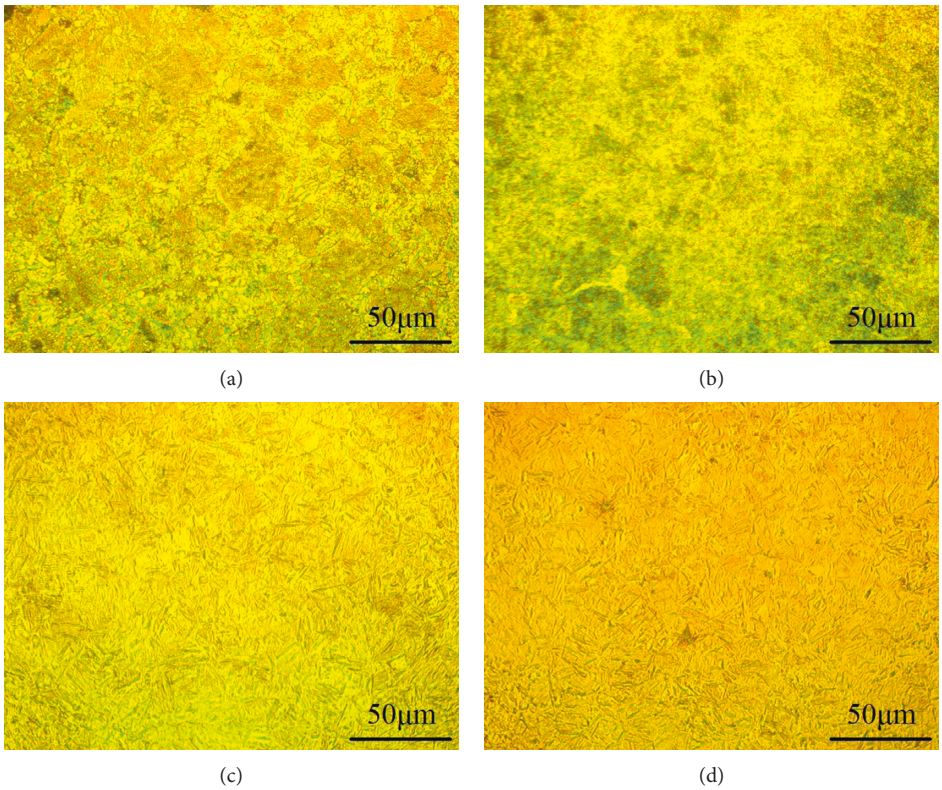

Figure 3: The metallographs of 34CrNiMo6 steel with different ratios of Al to N. (a) No Al element added. (b) The ratio of Al to N is 2.2. (c) The ratio of Al to N is 2.8. (d) The ratio of Al to N is 3.6.

magnitude, whose difference can be neglected. Thus, the content of Al is the most important factor on the ratio of Al to N.

The metallographs of 34CrNiMo6 steel with different ratios of Al to N are shown in Figure 3 to reflect the evolutions of average grain size with the content of aluminum.

As shown in Figure 3, the average grain size becomes greater first and then becomes smaller with the ratio of Al to N increasing. The grain size numbers of microstructures of all samples meet the criterion, which are all greater than 6.

Because the grain boundaries are used to provide an obstacle to dislocation movements, reducing the grain size could decrease the dislocation motion, so the strength of the metal significantly increases [19]; namely, the smaller the average grain size is, the better the mechanical properties the material have. That is to say, the strength and impact toughness of 34CrNiMo6 steel can be improved with refinement of the prior austenite grain size.

During the evolution process, the existence of Al element could make AlN precipitate at the austenite grain boundary, which could restrain the growth of grain via pinning effect at relatively low temperature. In contrast, the complete dissolution of these precipitates will cause large grain growth at relatively high temperature. Accordingly, this will cause a difference between the grain size at high deformation temperature (large grains) and grain size that was formed at low deformation temperatures (small grains). The precipitation can be observed from Figure 4, where the precipitation of aluminum nitride particles is the most likely reason for that. If Al is present with nitrogen, aluminum nitride particles will be formed, which may also inhibit austenite grain growth at high temperature. So, the experiments with different ratios of Al to N of the 34CrNiMo6 steel are carried out to clarify the conclusion. The mechanical property of 34CrNiMo6 steel reaches the peak at the ratio of Al to N equal to 2.8. Then, the mechanical property reduces

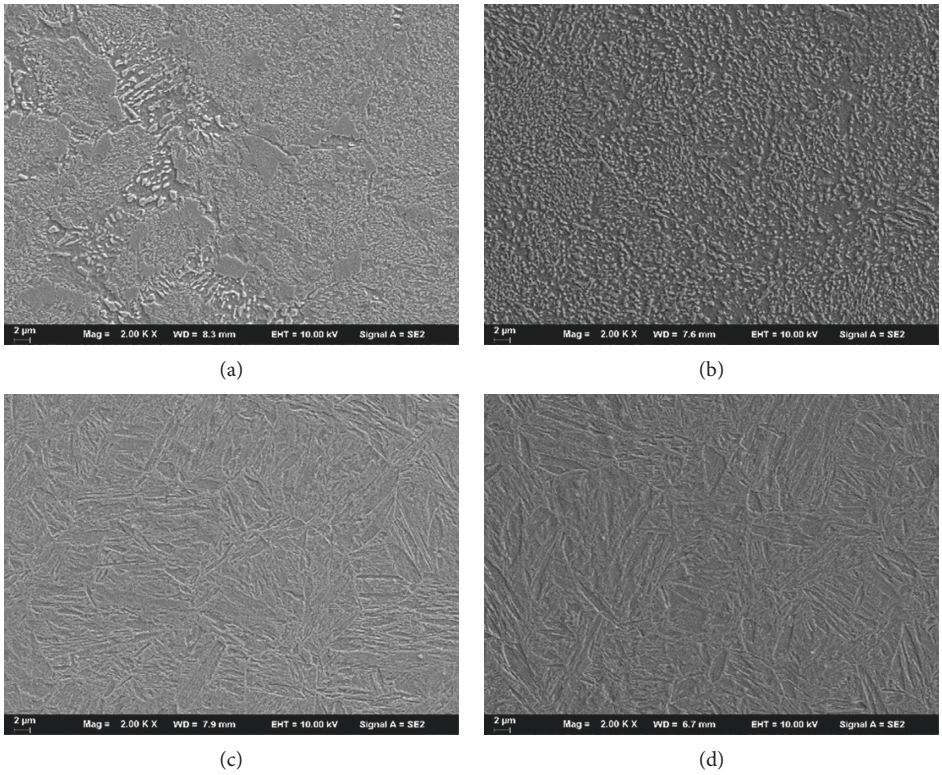

Figure 4: The metallographs of 34CrNiMo6 steel with different ratios of Al to N. (a) No Al element added. (b) The ratio of Al to N is 2.2. (c) The ratio of Al to N is 2.8. (d) The ratio of Al to N is 3.6.

at the ratio of Al to N equal to 3.6. However, the 34CrNiMo6 steel is a medium carbon steel which can be killed really fast during the secondary refining due to the high content of dioxide elements such as carbon, manganese, and silicon that reacts with oxygen, producing low content of dissolved oxygen in the steel. Moreover, the alloy elements such as Mo, V, and Cr also react with oxygen element, which could make the reduction of dissolved oxygen in 34CrNiMo6 steel. The process of secondary refinement is performed to refine the microstructures with deoxidation reaction. The 34CrNiMo6 steel in this study has total oxygen and nitrogen content of less than 25 ppm and 80 ppm, respectively. In Figure 4, size, shape, and dispersion of nonmetallic inclusions in the 34CrNiMo6 steel are shown.

4. Conclusions

This paper investigates the influence of the microalloying elements of 34CrNiMo6 steel on the microstructure and mechanical properties, especially Al and N elements. Then, testing of the tensile strength, yield strength, elongation after breakage, and impact absorbing energy under the different conditions is carried out to compare the mechanical properties of materials. The following conclusions can be drawn based on the experimental results:

(1) All the mechanical properties, tensile strength, yield strength, and elongation after breakage, increase firstly and then decrease with the content of aluminum increasing. The values of tensile strength, yield strength, and elongation after breakage reach the peak at about 0.02 wt.%.

(2) The mechanical properties of 34CrNiMo6 cannot meet the requirements $Rm \geq 1100$ MPa and $Re \geq 1000$ MPa when there is no Al adding. By contrast, the tensile strength and yield strength both could meet the requirements when the content of Al is from 0.016 wt.% to 0.027 wt.%.

(3) The impact absorbing energy increases firstly and then decreases with the content of aluminum increasing both at test temperature 20°C and −40°C. Compared with the impact absorbing energy at 20°C, Al element has a greater impact on the impact absorbing energy.

(4) The mechanical property of 34CrNiMo6 steel reaches the peak at the ratio of Al to N equal to 2.8. Then, the mechanical property reduces at the ratio of Al to N equal to 3.6, which may be the result of pinning effect of aluminum nitride.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

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