Original Research Article

Research on the wear resistance and microstructure change of 42CrMo based on deep cryogenic treatment

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Abstract: In this paper, 42CrMo steel is used as the object, the influence of different cryogenic treatment processes on the wear resistance of the material is explored by the wear rate. The morphology of wear scar, microstructure and phase composition were analyzed, and the mechanism of the influence of cryogenic treatment on wear resistance was summarized. The results show that the cryogenic treatment can significantly improve the wear resistance of the material, and the relative wear resistance is the highest compared with 1.35 times of the comparison group. After cryogenic treatment, the hardness of the sample was significantly improved, and the maximum increase was 4.0HRC. Cryogenic treatment has obvious influence on the microstructure of the material, which can promote the transformation of the retained austenite of the material, reduce its content, promote the transformation of coarse martensite structure, refine the martensite structure, thereby improve the hardness of the material and promote the fineness. The formation of carbides has a positive effect on the improvement of the wear resistance of the materials.

Keywords: Alloy steel; Cryogenic treatment; Wear resistance; Microstructure analysis

1. Introduction

42CrMo alloy steel has very high strength and good wear resistance, generally used in the manufacture of high strength requirements, wear and tear of large forging workpiece. At present, most of the domestic mining pick-type interceptor teeth use 42CrMo as the material of interceptor teeth. According to the statistical results of dozens of samples sampled from the coal mine site, the failure forms of the interceptor teeth are wear of the tooth body, chipping alloy pieces, dropping alloy head, tooth body fracture, etc., and its main failure form is wear[1].

Cryogenic treatment is a material treatment technology developed on the basis of conventional cold treatment technology to improve the mechanical properties of metallic materials. By liquid nitrogen refrigeration, the temperature is reduced to the test requirement temperature (minimum -196 °C) at a set rate of cooling, held for a period of time, after which it is returned to room temperature, usually followed by tempering treatment[2]. Cryogenic treatment puts the specimen in a box relatively isolated from the outside world so that it is as far as possible not to heat exchange with the outside world, through the temperature sensor placed in the box, controls the control switch at the other end of the sensor so that the temperature in the deep-cooling box is maintained at the test temperature for a period of time, in order to achieve the purpose of changing the internal organization of the material, so as to improve the mechanical properties of the material[3-4]. The transformation of residual austenite to martensite by deep cooling treatment reduces its content and provides potential nucleation sites for nanoscale carbides, which precipitate out of the martensite after subsequent heat treatment, and the precipitation of these carbides results in an increase in the hardness, toughness and wear resistance of the material[5]. Cryogenic treatment uses liquid nitrogen as the cooling medium, which is derived from air and does not cause any pollution to the environment in the process of use, which belongs to green manufacturing[6]. According to the research results in recent years[7-9], it is known that the arrangement of deep-cooling treatment between quenching and tempering has a significant effect on the improvement of material properties, which is better than the arrangement of deep-cooling treatment after tempering.

2. Experimental materials and methods

In this study, a 40 (mm) 42CrMo bar was cut into 40*10 (mm) discs as a specimen for wear test using CNC wire cutting machine DK7732C, the chemical composition of 42CrMo is shown in **Table 1**[10] and the heat treatment process of the specimen is shown in **Table 2**.

Table 1. Chemical composition of 42CrMo steel(wt%).

Element	C	Cr	Mn	Si	Mo	S
Content	0.38-0.45	0.9-1.2	0.5-0.8	0.17-0.37	0.15-0.25	≤0.035

Table 2. Heat treatment of test samples.

Sample	Heat treatment process
1	quenching (650℃×20min+850℃×10min) +tempering (250℃×120min)
2	quenching+cryogenic treatment (-80℃×1440min) +tempering
3	quenching+3 times cryogenic treatment (-80℃×1440min) +tempering
4	quenching+cryogenic treatment (-160℃×1440min) +tempering

To meet the requirements of surface roughness, the surface of the specimen was ground on a M7130 surface grinder, so that the final surface of the specimen meets the requirements of Ra ≤ 0.8 μm. In this paper, in the process of investigating the effect of deep cooling temperature on the wear properties of 42CrMo alloy steel, the specimens were subjected to wear test, hardness test, abrasion mark morphology analysis, microstructure analysis test (SEM) and XRD test.

Wear test will be divided into 3 groups in the CFT-I type multi-functional friction and wear tester on the specimen dry friction test, experimental parameters are shown in **Table 3**. The experimental principle is shown in **Figure 1**. wear form of the ball and disk, the diameter of the ceramic ball of the abrasion of 5 mm. wear test is completed, the wear specimens with acetone solution for ultrasonic cleaning, in the CFT-I-type surface properties of the material on the integrated tester to measure the wear volume, the roughness of its identification The accuracy of the recognition of roughness can reach 0.1μm, 3 specimens in each group, and each specimen was measured 5 times. After the wear of the specimen with CNC wire cutting machine DK7732C respectively in the abrasion marks and non-abrasion marks cut out 5 * 5 * 10 (mm) cube specimens, will not contain abrasion marks cubes using PG-1 type metallographic polishing machine for polishing, 4% nitric acid alcohol for corrosion. The changes in the morphology and organization of the abrasions were observed in a VEGA 3 SBH fully automated tungsten filament scanning electron microscope (SEM), and XRD tests were performed using a MiniFlex600 benchtop X-ray diffractometer.

Table 3. Wear test parameters.

Test material	Test speed (r/min)	Test load (N)	Wear radius (mm)	Wear time (min)
42CrMo	1024	49	7	40

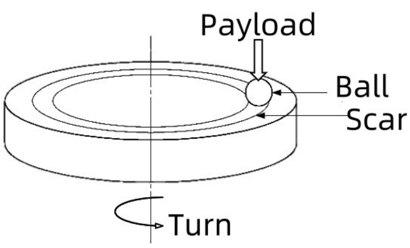


Figure 1. Experimental principle of wear test.

3. Results and analysis

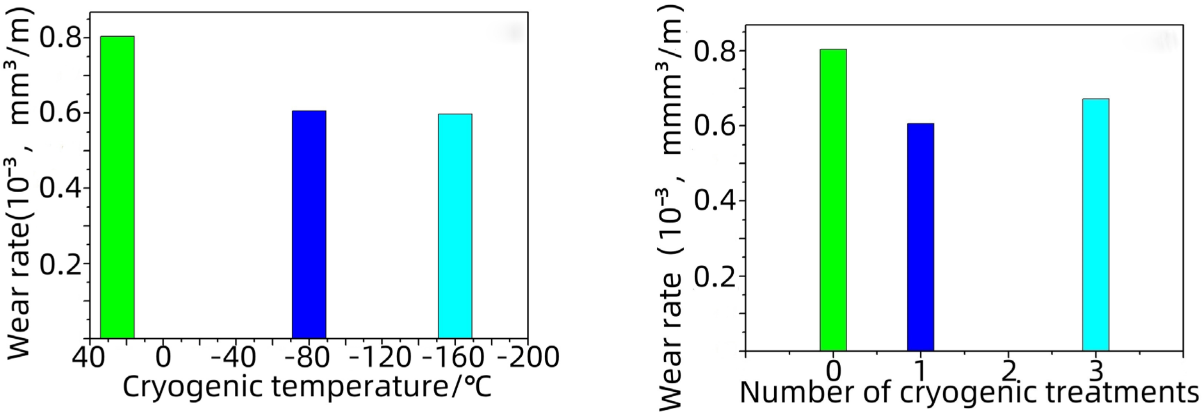
3.1. Wear test results and analysis

The wear rate was calculated according to equation (1) [11].

$$W_r = \Delta V / L \quad (1)$$

In the formula, *Wr* is the wear rate of the material, measured in mm3/m; *Δ V* is the wear volume of the material, measured in mm^3; *L* is the wear distance, measured in millimeters.

As can be seen from **Figure 2(a)**, comparing specimens No. 1, No. 2 and No. 4, the wear rate of specimen No. 2 is lower than that of specimen No. 1 in the comparison group, and the wear rate of specimen No. 4 is the smallest; when the temperature is from 25°C to -80°C, the wear rate changes faster with the reduction of temperature; when the deep-cooling is lowered from -80°C to -160°C, the wear rate is not affected by the temperature of deep-cooling obviously, and its wear rate is slightly lower than that of specimen No. 2. Comparing the specimens of the comparison group with the other two groups, it is found that the deep cooling treatment can substantially reduce the wear rate of the specimens, and the lower the temperature, the smaller the wear rate. From **Figure 2(b)**, it can be seen that comparing specimens No. 1, No.2 and No. 3, the abrasion resistance of the specimens after deep-cooling treatment is greatly improved compared with that of the specimens without deep-cooling treatment, but the abrasion rate of specimen No. 2 is lower than that of specimen No. 3, which shows that the cyclic deep-cooling treatment can deteriorate the abrasion resistance of the specimens.



(a) Effect of Cryogenic temperature (b) The number of cryogenic treatments affects

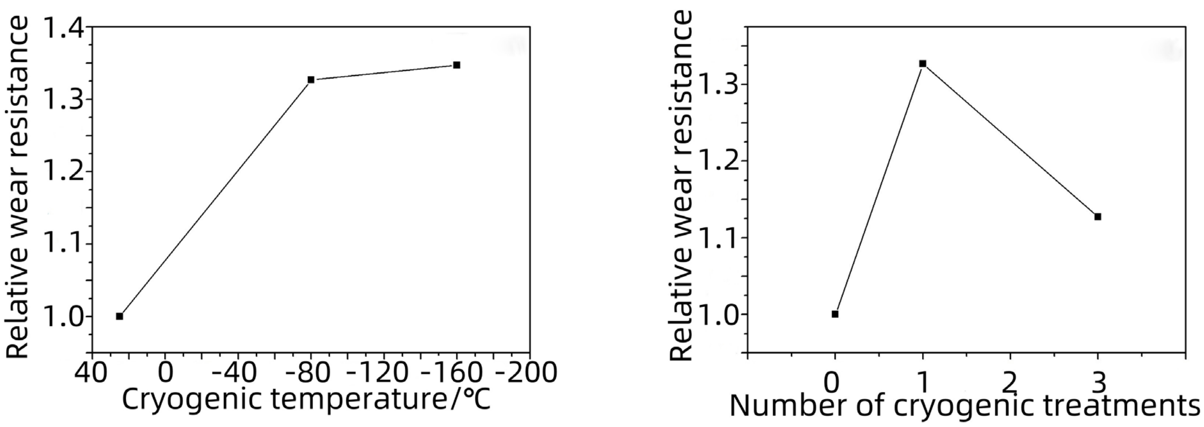
Figure 2. Effect of cryogenic temperature on the wear rate of 42CrMo alloy steel.

Figure 3 shows the quantitative analysis of the degree of improvement in wear resistance under different cryogenic temperatures, namely relative wear resistance. Relative wear resistance is a characterization method of material wear resistance, usually referring to the ratio of the wear amount of two materials A and B under the same wear conditions. The calculation formula (2)[12] is as follows:

$$\varepsilon = WA/WB \quad (2)$$

In the formula, *ε* is the relative wear resistance of the material; *WA* is the wear volume of the standard (or reference) specimen, measured in mm^3; *WB* is the wear volume of the test sample, measured in mm[3].

The wear volume of the standard specimen for this group of tests represents the wear volume of the un-deep-cooled specimen, and the wear volume of the specimen to be tested represents the wear volume of the specimen at different deep-cooling temperatures.



(a) Effect of Cryogenic temperature (b) The number of cryogenic treatments affects

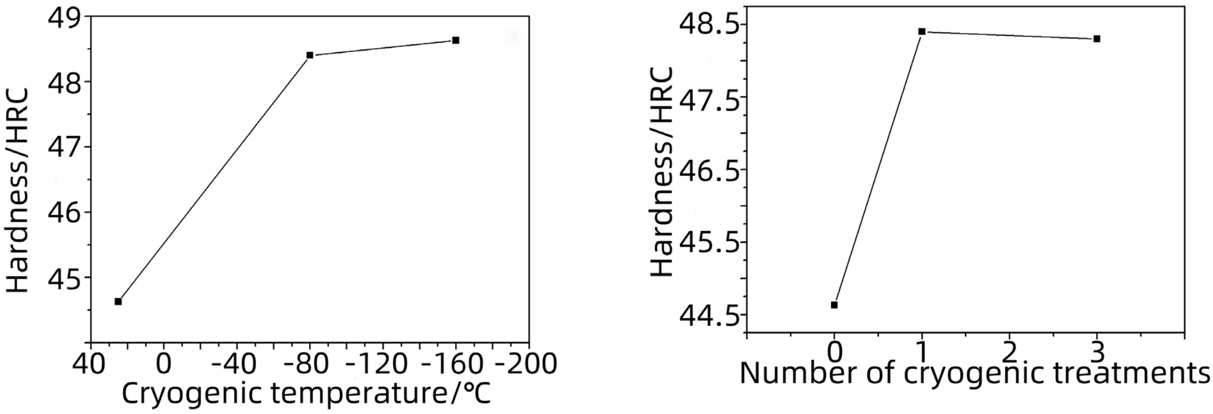
Figure 3. Effect of cryogenic treatment on relative wear resistance of 42CrMo alloy steel.

As can be seen from **Figure 3(a)**, comparing specimens No. 1, No. 2 and No. 4, the relative abrasion resistance of specimen No. 2 is 1.33 times that of the comparison group, and there is a very obvious improvement in the material abrasion resistance, and when the temperature of the deep-cooling treatment reaches -160°C, the abrasion resistance of specimen No. 4 is 1.35 times that of specimen No. 1; the relative abrasion resistance of the cold treatment of -80°C is very quickly improved in comparison to that of the comparison group, and the change in the relative abrasion resistance of specimen No. 2 and the relative abrasion resistance of specimen No. 4 slows down. The relative wear resistance of specimen No. 2 is very fast compared with the comparison group, while the relative wear resistance of specimen No. 4 is slower than that of specimen No. 2, and the change of material properties is also slower. From **Figure3(b)**, the relative abrasion resistance of specimen No. 2 reaches the peak of this test, which is 1.33 times of that of specimen No. 1; however, with the increase of the number of cold treatment cycles, the relative abrasion resistance of the specimen shows a decreasing trend, but it is also higher than that of specimen No. 1, and the relative abrasion resistance of specimen No. 3 is 1.13 times of that of specimen No. 1. Therefore, the relative abrasion resistance does not become better with the increase of the number of cycles; on the contrary, multiple deep cold treatments rather reduce the relative abrasion resistance of the material.

3.2. Hardness testing

Hardness can not be regarded as a single physical quantity, it is related to the strength and elasticity of the material, but also affected by the plasticity and toughness of the material. The performance of the material depends largely on the size of the material hardness, hardness is the material resistance to external forces and plastic deformation, the ability to be destroyed, is to test the performance of metal materials is an important standard. This paper adopts the indentation method to measure the hardness value of each group of specimens, the instrument used is HRC-150A Rockwell hardness tester. Before the test, the specimens were firstly polished with sandpaper to make the surface flat before the test, and then cleaned with acetone solution in ultrasonic wave to ensure that the surface stains were removed, and the final measurement was made by using HRC-150A Rockwell hardness tester. Each specimen was evenly tested 5 times, removing the maximum and minimum values away from the average, and then taking the average value of each group of 4 specimens as the final hardness value of the group of specimens.

The variation of hardness with deep cooling temperature is shown in **Figure 3** (25 ℃ indicates the specimen without deep cooling treatment). From **Figure 4(a)**, it can be seen that comparing specimens No. 1, No. 2 and No. 4, the hardness of specimen No. 4 reaches 48.6 HRC, which is 4 HRC higher compared with that of specimen No. 1, which is a very obvious effect; the further reduction of the deep cooling temperature will make the hardness of Talent material gradually increase. In **Figure 4(b)**, the hardness of sample No. 2 is 48.4 HRC, while the hardness of sample No. 3 is reduced by 0.1 HRC compared with that of sample No. 2, which indicates that the cyclic deep cooling treatment will make the hardness of the specimen deteriorate, but the effect is relatively small. The trend of the effect of the number of deep cooling on the hardness of the specimens verifies the variation of the relative wear resistance with the number of deep cooling.



(a) Effect of Cryogenic temperature (b) The number of cryogenic treatments affects

Figure 4. Effect of cryogenic treatment on hardness of 42CrMo alloy steel.

3.3. Wear mechanism and wear mark morphology

Wear is the result of the combined mechanical and chemical action on the surface of a material, and the wear result is often due to multiple wear mechanisms. Since the tests in this paper involve adhesive wear, oxidative wear and abrasive wear, the mechanisms of these three types of wear are briefly described here.

(1) Mechanism of adhesive wear

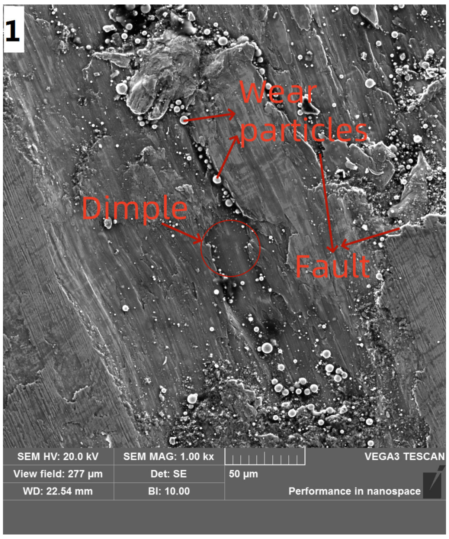
Adhesive wear is the most common form of wear in machining. Adhesive wear first appears in the position of the worst surface properties, by the two contact surfaces of the micro-convex body molecular forces interacting with each other, relative movement process, the two surfaces of the micro-convex body due to mechanical interaction force will occur shear phenomenon, making part of the micro-convex body on one side of the destruction of the adhesion of the other side; continue to friction, adhesion of micro-convex body will fall off and adhesion to the original side, or as a free The micro-convex body will fall off and stick to the original side or exist between the two friction surfaces as a free state.

(2) Oxidative wear mechanism

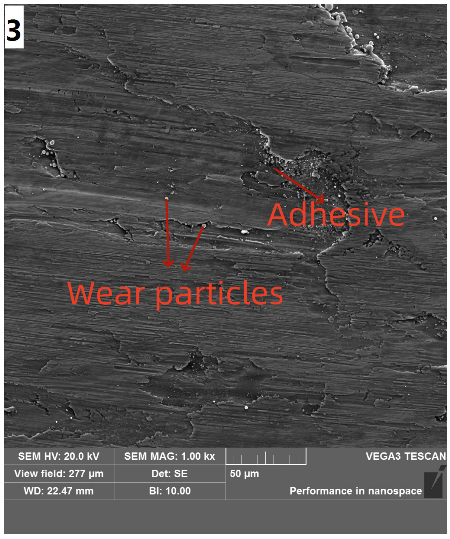
Oxidative wear in the two relative contact surface temperature is high when the most common type of wear mechanism. As almost all the friction occurs in the air, and metal materials encountered in high temperature and easy to be oxidized, material oxidation occurs after the reduction of surface properties, the role of subsequent mechanical movement so that the wear is aggravated. Oxide film also exists on the surface of the material at room temperature, but the relative motion of the contact will destroy it, and the temperature will increase the material will have an oxide film so that the cycle, the formation of oxidative wear.

(3) Abrasive wear mechanism

Abrasive wear is due to the material surface unevenness or wear process outside the hard particles flying into the form of wear, its main morphological manifestation of the surface scratches or even furrows appear. When there is abrasive wear on the relative wear surface, it leads to the shedding of wear particles on the surface, and so on, intensifying the wear. The formation of abrasive wear is mainly related to the hardness of the material, surface roughness and wear environment.



(a) Not Cryogenic treatment



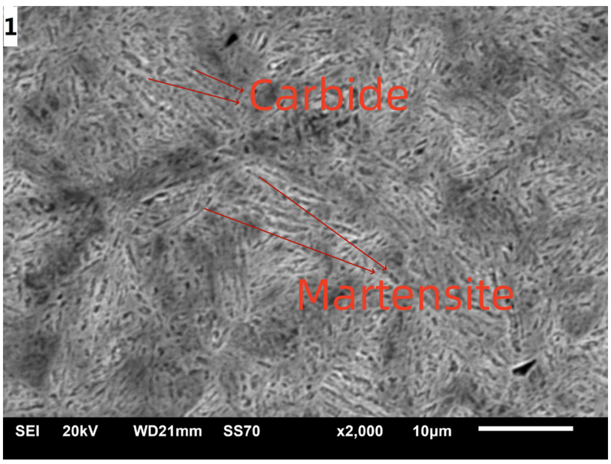
(b) After cryogenic treatment

Figure 5. Effect of cryogenic temperature on wear scar morphology of 42CrMo alloy.

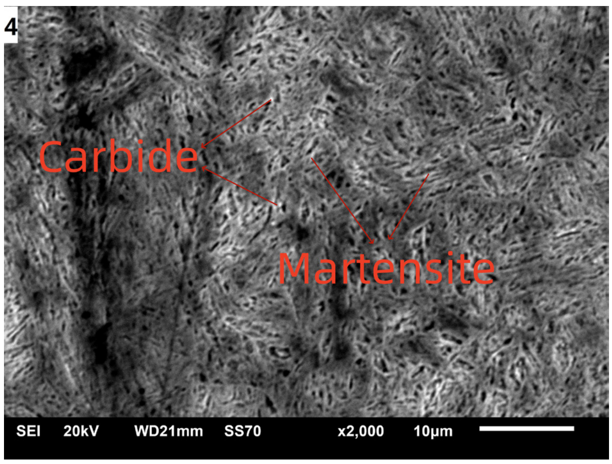
Figure 5 compares the micrographs of the specimen wear marks before and after the deep cold treatment. **Figure 5(a)** shows the No. 1 specimen without deep cold treatment, which has the most serious wear, with obvious plastic deformation and tearing of the surface layer of the wear mark part, as well as localized craters on the surface, accompanied by serious adhesion phenomena. Specimen wear surface material transfer occurred, resulting in a more serious furrow; and after -80 ℃ three times after deep cooling treatment of the No. 3 specimen, the depth of grinding relative to the other specimens is the shallowest, there is no furrow and tear phenomenon, the surface residues of very little abrasive debris, the above morphology of the abrasive marks indicate that the main form of wear of the No. 3 specimen is a slight form of adhesive wear and accompanied by a certain degree of abrasive grain wear. The microscopic morphology of the abrasion marks well verified the effect of deep cooling treatment on the wear resistance.

3.4. Material microstructure analysis

Figure 6 shows the microstructure of the specimen before and after deep cooling treatment. As seen in **Figure 6(a)**, the specimen No. 1 of 42CrMo material after quenching and tempering treatment is organized as tempered martensite and residual austenite.



(a) Not Cryogenic treatment



(b) After cryogenic treatment

Figure 6. Effect of cryogenic temperature on microstructure of 42CrMo alloy steel.

The specimen in the conventional quenched state after conventional tempering treatment, the carbides grow into spherical morphology with vacuolar nuclei and are distributed in the martensite within the laths and at the boundaries. The organization of 42CrMo steel is mainly pearlitic and ferrite, with a large proportion of pearlitic, and the alloying element Cr in the material causes the grain to be refined, because the Cr in 42CrMo combines with the C in the steel to form carbides, and these Carbides will precipitate at grain boundaries, preventing grain growth, grain refinement, pearlitic lamellar spacing gradually reduced, the strength of 42CrMo steel increased. Deep cooling treatment can promote the transformation of residual austenite, chromium and carbon elements formed carbides will also be affected by the deep cooling treatment and precipitation increased, so as to improve the wear resistance of the material. In this group of tests, the organization of specimen No. 4 is the most uniform and the refinement is also the most obvious. It indicates that the deep cooling temperature has the most obvious effect on the wear resistance of 42CrMo steel. Deep cooling treatment process residual austenite will be a large number of martensite transformation, martensite organization produces a large number of dislocations, precipitation of a large number of carbon elements, tempering treatment, the internal reorganization of the material occurs, the unstable carbon elements and the relevant elements combined, so as to become a relatively stable carbide precipitation, deep cooling treatment of the specimen's organization is obviously refined, and in the martensite on the precipitation of fine carbides.

3.5. XRD analysis

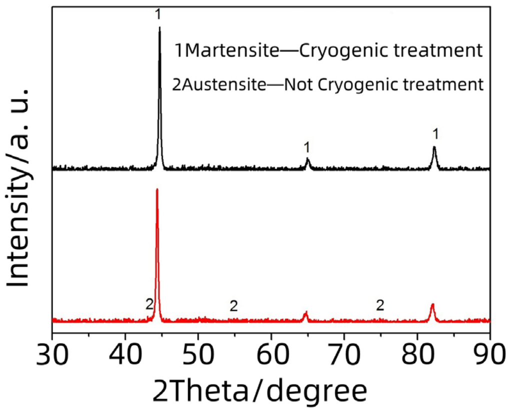


Figure 7. XRD of 42CrMo before and after cryogenic treatment.

42CrMo steel has a certain percentage of residual austenite transformed to martensite by the action of deep cooling treatment. **Figure 7** shows the XRD diagrams of 42CrMo steel before and after the deep cooling treatment, as can be seen from the figure, the main peak of the material appeared in the vicinity of 45º, compared with the group of 42CrMo steel, the main peak of the martensite and residual austenite, after the deep cooling treatment, the martensite diffraction peak of the specimen has a significant enhancement of the austenite peak gradually weakened or even disappeared. This is because 42CrMo just after quenching, due to quenching will not make all the austenite transformation, and deep cooling can provide the transformation of power, so that the residual austenite to martensite transformation, so that the peak of the martensite phase has obviously strengthened, and the phase peak of the residual austenite weakened or even disappeared. The test illustrates the promotion effect of deep cooling treatment on the transformation of residual austenite to martensite in the organization of 42CrMo steel.

4. Conclusion

(1) 42CrMo after deep-cooling treatment of the specimen compared to the traditional heat treatment speci-

mens, wear resistance are significantly improved; relative wear resistance with the cooling temperature changes in the early stage of faster, wear resistance enhancement is obvious, the later with the cooling temperature into the deep-cooling treatment stage of the change becomes slower, after -160 ℃ deep-cooling treatment of the relative abrasion resistance of the most increased to the traditional heat treatment of 1.35 times.

(2) The material is 48.6 HRC after -160 ℃ deep cold treatment, compared with the traditional heat treatment to improve 4.0 HRC; the increase in hardness to a certain extent is conducive to the improvement of wear resistance of 42CrMo material.

(3) 42CrMo after deep cooling treatment, the material microstructure changes are very obvious. With the reduction of deep cooling temperature, the material in the martensite refinement obvious, the number of lamellar martensite increased, coarse tempered martensite and residual austenite is reduced accordingly, and deep cooling process accompanied by fine carbide precipitation.

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