Effect of Cryogenic Treatment on Microstructure, Mechanical Properties and Distortion of Carburized Gear Steels

Yongming Yan 1,* , Ke Liu 2, Zixiang Luo 3, Maoqiu Wang 1 and Xinming Wang 3

1 Institute of Special Steel, Central Iron and Steel Research Institute, Beijing 100081, China; maoqiuwang@hotmail.com
2 Jianglu Machinery and Electronics Group Co., Ltd., Xiangtan 411100, China; liuke820x@126.com
3 School of Material Science and Engineering, Xiangtan University, Xiangtan 411100, China; 20192100149@xtu.edu.cn (Z.L.); wangxm@xtu.edu.cn (X.W.)
* Correspondence: yanyongming@nercast.com; Tel.: +86-010-62182728

Abstract: The effects of cryogenic treatment and low temperature tempering on the microstructure, mechanical properties and distortion of the 20Cr2Ni4A and 17Cr2Ni2MoVNb carburized gear steels were investigated. The results showed that the case hardness of the experimental steels was increased after the cryogenic treatment, due to the decrease of the retained austenite content and the precipitation of the tiny carbides. The wear resistance of the two steels after cryogenic treatment was improved, although the wear mechanisms were different for 17Cr2Ni2MoVNb and 20Cr2Ni4A steels. The distortion of the Navy C-ring specimens underwent shrinkage before expansion during the cryogenic process, and the distortion of 17Cr2Ni2MoVNb steel was smaller than that of 20Cr2Ni4A steel.

Keywords: gear steel; cryogenic treatment; carburizing; retained austenite; wear

1. Introduction

Heavy-duty gears are widely used in large-scale mechanical transmission parts in industries such as automobile aerospace and military industries due to their large bearing load and high transmission power. The 20Cr2Ni4A steel has good comprehensive mechanical properties after carburizing, so it is widely used in the manufacture of military load gears [1,2]. However, due to its high hardenability and large grain sizes, the manufactured gears made of 20Cr2Ni4A steel often suffer from serious heat treatment distortion and large fluctuation range in fatigue lives [3,4]. Therefore, it is of great significance to find the materials with higher fatigue life, finer grain sizes, and smaller heat treatment distortion to replace 20Cr2Ni4A steel.

The 17Cr2Ni2MoVNb steel was developed on the basis of 18CrNiMo7-6 steel, which has low carburizing heat treatment distortion, high strength, toughness and fatigue properties, being one of the potential materials for high-strength carburizing steel. Similar to 20Cr2Ni4A steel, 17Cr2Ni2MoVNb steel still contains a large amount of chromium and nickel, elements, which may increase the stability of retained austenite in the carburized layer after carburizing and air cooling [5,6]. Reheating and quenching cannot reduce the content of retained austenite, and the hardness cannot be further improved to meet the increasing design requirements. In addition, the retained austenite may transform into martensite under strain during service, causing dimensional changes and redistribution of stress, and it may also cause grinding cracks during grinding and finishing. It has been reported that the cryogenic treatment can promote the transformation of retained austenite into martensite and improve mechanical properties including hardness and wear resistance [7–12]. Previous research work on 17Cr2Ni2MoVNb steel was mainly focused on the influences of process parameters such as carburizing temperature, quenching temperature and tempering temperature on the structure and properties [13–15]. There are no reports on the effect of cryogenic treatment on microstructure and mechanical properties...
of 17Cr2Ni2MoVNb steel. In this experiment, the effect of cryogenic treatment on the microstructure, microhardness, and wear resistance of carburized steel is investigated.

2. Materials and Methods

2.1. Materials and Heat Treatment

The industrially-manufactured hot-rolled bars of 100 mm in diameter for 20Cr2Ni4A and 17Cr2Ni2MoVNb steels, with the compositions as listed in Table 1, were used as the experimental steels.

Table 1. Chemical compositions of the experimental steels (wt.%).

| Steel             | C    | Si  | Mn  | Cr  | Ni  | Mo | Nb | V   | Fe  |
|-------------------|------|-----|-----|-----|-----|----|----|-----|-----|
| 20Cr2Ni4A         | 0.21 | 0.25| 0.48| 1.45| 3.55| -  | -  | -   | Bal.|
| 17Cr2Ni2MoVNb     | 0.17 | ≤0.4| 0.77| 1.68| 1.60| 0.29| 0.04| 0.10| Bal.|

Hot-rolled bars of the experimental steels were machined as Navy C-ring specimens with the shape and size diagram as shown in Figure 1. Figure 2 shows the carburizing and heat treatment processes of the experimental steels. The C-ring samples were carburized in an Ipsen multi-purpose carburizing furnace. The carburizing medium was propane, and the carburizing temperature was 930 °C. The total time for the carburization process was about 6.7 h. The carbon potential (Cp) value was 1.05% during the first 6 h, and it was changed to 1.00% during the last 0.7 h. Then the samples were air cooled. The samples were then tempered at 620 °C for 4 h and air cooled. The samples were subsequently held together at 800 °C for 1 h and then quenched in oil. Then the quenched samples were treated by three kinds of process. The QTCT sample was tempered at 150 °C for 4 h, then cryogenic treated at −196 °C for 1 h, and tempered at 150 °C for 2 h. The QCT sample was cryogenic treated at −196 °C for 1 h and tempered at 150 °C for 2 h, and the QT sample was only tempered at 150 °C for 2 h. The detail process parameters are listed in Table 2.

Figure 1. Shape and dimensions of the Navy C-ring specimens.
Table 2. Different heat treatments and the sample codes.

| Steel          | Sample Code | Description of Heat Treatment Cycles | Quenching | Temperature      | Cryogenic Treatment | Temperature |
|----------------|-------------|-------------------------------------|-----------|------------------|---------------------|-------------|
| 20Cr2Ni4A      | 20-QT       |                                     | 800 °C, 1 h | 150 °C, 4 h     | –                   | –           |
|                | 20-QTCT     |                                     | 800 °C, 1 h | 150 °C, 4 h     | 196 °C, 1 h         | 150 °C, 2 h |
|                | 20-QCT      |                                     | 800 °C, 1 h | –                | 196 °C, 1 h         | 150 °C, 2 h |
| 17Cr2Ni2MoVNb  | 17-QT       |                                     | 800 °C, 1 h | 150 °C, 4 h     | –                   | –           |
|                | 17-QTCT     |                                     | 800 °C, 1 h | 150 °C, 4 h     | 196 °C, 1 h         | 150 °C, 2 h |
|                | 17-QCT      |                                     | 800 °C, 1 h | –                | 196 °C, 1 h         | 150 °C, 2 h |

2.2. Microstructural Characterization

The microstructural observations were carried out using optical microscopy (OM, ZEISS) and scanning electron microscopy (SEM, ZEISS, EVO-MA10). The samples were cut into 10 × 10 × 10 (mm³) cubes by electric spark wire and then polished by 400, 600, and 800 mesh sandpaper after inlay. Etching was done using 4% nitric solution for a period of 10 s, followed by rinsing using water and drying using a blower. The content of retained austenite was measured using X-ray diffractometer (Make: Rigaku, Model: D/MAX-2500/PC) with the target material for Cu power for 18 kW, with the scanning speed for 1°/min and the diffraction angle from 40° to 90°.

2.3. Tests for Hardness and Wear Resistance

The hardness distribution along the depth from the carburized surface was tested using a HuaYing tester (model HVT-1000A, the indenter is diamond) under an applied load of 0.987 g for 10 s. In order to improve accuracy, the hardness values were taken at 5 distinct points and the values were averaged. Friction and wear experiments were carried out using CFT-1 comprehensive tester for material surface performance. The wear mode was reciprocating; the friction surface of the sample was carburized surface; the friction pair was Si₃N₄ ceramic ball in 3 mm, and the friction conditions were as follows: the dry friction at 30 °C, a load of 30 N, a speed of 500 times/min and a reciprocating distance of 5 mm. The wear volume was also tested by the CFT-1 comprehensive tester. A wear mark was measured in the upper, middle and lower areas, and each measurement was taken.
three times. The final average value was the wear volume, and then the wear rate was tested according to the Equation (1).

\[
W_r = \frac{\Delta V}{L}
\]  

(1)

where \(W_r\) is the wear rate (mm\(^3\)/m), \(\Delta V\) is the wear volume (mm\(^3\)) and \(L\) is the total wear length (m). Distortion of the Navy-C ring specimens in each stage of the cryogenic processes was measured by the gap distance using vernier calipers, with six times of measurements to take the average value [16].

3. Results

The carbon concentration gradients of the quenched experimental steels are shown in Figure 3, from which it can be seen that the 20Cr2Ni4A and 17Cr2Ni2MoVNb steel have similar carbon concentration distribution and have similar carburizing characteristics under the same carburizing process. The depth of carburizing layer of both steels was (1.4 ± 0.1) mm. The hardness distribution of the carburized layer of the experimental steel after quenching and tempering is shown in Figure 3b. It is obvious that due to the decarburization phenomenon, internal oxidation occurs on the surface of the carburized layer, and this defective organization leads to a decrease in the carbon concentration and microhardness on the surface of the sample carburized layer [17]. 17Cr2Ni2MoVNb steel had a maximum hardness of (730 ± 5) HV and a hardness of (450 ± 5) HV in the center with low-carbon martensitic organization. In contrast, the 20Cr2Ni4 steel had a maximum hardness of (717 ± 5) HV with a hardness of (461 ± 5) HV in the center having low-carbon martensite. Evidently, the hardness declines continuously from the surface to the center of both steels, because of the carbon content keeps falling from surface to center; 20Cr2Ni4A steel has a higher core hardness due to its higher carbon content. 17Cr2Ni2MoVNb steel has a fine surface; carbide organization helps to increase the hardness value of the steel, which is beneficial to improve wear resistance [18].

![Figure 3](image_url)

**Figure 3.** C content distributions (a) and hardness distribution (b) in carburized layer of experimental steels after quenching and tempering.

The SEM microstructure images of 20Cr2Ni4A and 17Cr2Ni2MoVNb steels in the QT state without cryogenic treatment are shown in Figure 4. The microstructure of the experimental steels in the carburized layer consists of martensite, retained austenite and carbides (Figure 4a,b). The fine carbides are uniformly distributed, and the carbides of 17-QT are more and larger at the grain boundaries than those of the 20-QT sample. The color redefinition of the photographs was obtained by PS software in Figure 4c. The carbide content of the samples was then expressed as a relative frequency of carbide distribution using Image-Pro Plus software [19]. (The sampling position is the sample carburized layer at 0.2 mm position from the surface.) Few differences were observed in the microstructure
of the matrix of the two steels shown in Figure 4e,f. Based on OM Microstructure grain photos, two steel grain size classes were calculated using the cut-off point method, and the results were 8.3 for 17-QT and 7.2 for 20-QT.

Figure 4. SEM microstructure: (a) the carburized layer of 17-QT sample, (b) the carburized layer of 20-QT sample; (c) enlargement of the view in (a), (d) Image-pro calculation schematic of (c); (e) the matrix of 20-QT sample; (f) the matrix of 17-QT sample.

3.1. Effect of Cryogenic Treatment on Microstructure

Figure 5 shows the SEM images of the experimental steels under different processes. It can be seen that the matrix microstructure of both steels consisted of tempered martensite, with spherical carbides uniformly distributed in the carburized layer matrix as well as a small amount of retained austenite, and the core was low-carbon lath martensite. The carbides were distributed at the grain boundaries in the 17-QTCT sample. Comparing the carbides in Figure 6 with that in Figure 5, the QTCT samples had more carbides in the carburized layer, and more small spherical carbides precipitated on the high-carbon tempered martensite matrix than the QT samples, while the carbides in the QCT samples showed few differences with those in the QT samples [20]. The 17-QTCT and 20-QTCT samples had the most amounts of carbide precipitation. More diffusely distributed carbides were obtained for the 17QCT and 20QCT samples. 17-QCT samples showed an increase
in carbide size. This is due to the possible transformation of some retained austenite to martensite during cooling, which enhances the thermodynamic driving force for carbon atom precipitation. In addition, the diffusion of carbon atoms became more difficult at low temperatures, and the diffusion distance became shorter [21]. Thus, a large number of dispersed ultrafine carbides were precipitated on the martensite.

![Figure 5. SEM images of the carburized layer in the 20-QTCT sample (a); in the 20-QCT sample (b); in the 17-QTCT sample (c); in the 17-QCT sample (d) and the matrix in the 20-QTCT sample (e); in the 20-QCT sample (f); in the 17-QTCT sample (g); in the 17-QCT sample (h).](image)

The relative frequencies of carbides were calculated by Image-pro software for the acquired SEM images, and the results are shown in Figure 6. The number and size of carbides in the samples were enhanced after cold treatment. The volume percentages of carbides obtained by the area percentage calculation of Image-pro software are 7.36% for 17-QT, 10.36% for 17-QTCT, 12.75% for 17-QCT, 6.17% for 20-QT, 9.2% for 20-QTCT, and 11.8% 20-QCT. This is due to the transformation of partially retained austenite during the cooling process to martensite, and the lattice constant of iron tends to contract, which increases the lattice distortion caused by the supersaturated carbon atoms and thus enhances the thermodynamic driving force for the precipitation of carbon atoms. At the same time, for QCT samples, the stress inside the sample is greater due to one less low-tempering process, resulting in more driving force for carbide precipitation. In addition, it is essentially difficult for the carbon atoms to move diffusely during the cold treatment process. As a result, a large number of dispersed ultrafine carbides precipitate on martensite [8,22].
20Cr2Ni4A and 17Cr2Ni2MoVNb steels undergo a change in chemical composition and microstructure from the surface to the matrix due to the change in C content after carburization. Equation (2) allows to calculate the \( M_s \) point of the core and the carburized surfaces [23]. The results show that the \( M_s \) points of the carburized surfaces of 17Cr2Ni2MoVNb and 20Cr2Ni4A steels are \((58 \pm 10) \, ^\circ C\) and \((42 \pm 10) \, ^\circ C\), respectively. The \( M_s \) points of the matrix of 17Cr2Ni2MoVNb and 20Cr2Ni4A steels are \((385 \pm 10) \, ^\circ C\) and \(~(355 \pm 10) \, ^\circ C\). Note that the influence of elemental Nb and V is not considered in the Equation (2), which leads to a larger \( M_s \) points in 17Cr2Ni2MoVNb steel.

\[
M_s \, (^\circ C) = 539-423C-30.4Mn-17.7Ni-12.1Cr-7.5Mo \tag{2}
\]

According to the Magee [24] equation, the amount of martensite formation can be expressed by Equation (3).

\[
f = 1 - \exp \left[ -\alpha \left( M_s - T_q \right) \right] \tag{3}
\]

where \( T_q \) is the specified temperature (usually the temperature of the quenching medium), and the experimental results of the literature [25] for Fe-C alloy steels with carbon mass fractions in the range of 0.37 to 1.11% had a value of \( 1.10 \times 10^{-2} \) for \( \alpha \).

Combining Equation (2) with Equation (3), it can be seen that an increase in C content leads to a decrease in \( M_s \). The value of \( f \) increases as the \( M_s \) point increases and decreases as the \( M_s \) point decreases. At the same time the amount of martensite formation influences to a certain extent the content of residual austenite. In order to obtain a more accurate retained austenite content, X-ray diffractometer was used to detect the retained austenite content. The XRD patterns of the carburized layer at 0.2 \((\pm0.05)\) mm from the surface and the content histogram of the retained austenite are shown in Figure 7. The fraction of the retained austenite was different, and it could be calculated from XRD results by Equation (4) [26].

\[
V_\gamma = \frac{1.4I_\gamma}{I_\alpha + 1.4I_\gamma} \tag{4}
\]

where \( V_\gamma \) is the volume fraction of retained austenite; \( I_\gamma \) is the mean integrated intensities of the austenite peaks including \( \gamma(111) \), \( \gamma(200) \) and \( \gamma(220) \); and \( I_\alpha \) is the mean integrated intensities of the martensite peaks including \( M/\alpha(110) \), \( M/\alpha(200) \) and \( M/\alpha(211) \).
Figure 7. XRD diffraction patterns in the carburized case of the experimental steel in different processes: (a) Histogram of residual austenite content, (b) XRD diffraction patterns.

In order to reduce the error, the lower angle peaks of \( \gamma (111) \) and \( M/\alpha (110) \) were neglected. The calculated contents of retained austenite were 19.23% for 17-QT, 13.1% for 20-QT, 10.7% for 17-QTCT, 9.15% for 17-QCT, 9.5% for 20-QTCT and 9.6% for 20-QCT, respectively. It is clearly observed from the histogram in Figure 7a that the content of retained austenite in both the steels is decreased to below 10% after cryogenic treatment, and the retained austenite in 17-QT is more than that of 20-QT before cryogenic treatment. After carburizing, a large amount of carbon and alloying elements were dissolved in the matrix, which significantly reduced the Ms point and a large amount of retained austenite could form in the carburized layer after carburizing and quenching. Through the cryogenic treatment, the retained austenite content in carburized layer of 17Cr2Ni2MoVNb steel was significantly reduced. However, the 17-QCT samples showed less residual austenite than the 17-QTCT samples. In addition, when the residual austenite content of steels was high after carburization, the cryogensics treatment transformed most of the residual austenite to martensite [27]. The 17-QCT sample has the most residual austenite transformed into martensite. By observing the XRD diffractogram in Figure 7b, it can be seen that the diffraction peaks of the 17-QCT sample were shifted more to the right than those of 17-QT, and the diffraction peaks of 20Cr2Ni4A steel were all shifted to the right compared with those of 17Cr2Ni2MoVNb steel, which was presumably caused by the lattice distortion.

3.2. Effect of Cryogenic Treatment and Tempering on Mechanical Properties

The in-depth hardness distribution curves of 17Cr2Ni2MoVNb and 20Cr2Ni4A steels under different processes are shown in Figure 8. Compared with the sample without cryogenic treatment, the samples through cryogenic treatment showed an increased hardness in the near-surface carburized layer, with the hardness increased by 102 HV for 17-QTCT and 122 HV for 17-QCT and by 13 HV for 20-QTCT and 34 HV for 20-QCT. The 17-QCT sample had a highest hardness at carburized layer than the other samples, while the 17-QT had a minimal content of retained austenite. Thus, the content of retained austenite was an important factor on the hardness of the carburized layer. The cryogenic treatment reduced the content of retained austenite and promoted the carbide precipitation in the carburized layer, leading to the increase in hardness. The depth of the carburized layer (at 550 HV) was almost the same for the samples. It can be seen that the cryogenic treatment did not evidently influence the effective carburized depth. The increase in hardness of the 17Cr2Ni2MoVNb steel through cryogenic treatment was more than that of 20Cr2Ni4A steel. It can be seen that the Ms point of 20Cr2Ni4A steel is lower than that of 17Cr2Ni2MoVNb steel. Quenched with the same quenching medium and temperature, 17Cr2Ni2MoVNb steel makes the martensite structure easier to obtain, and the hardness after quenching is higher (H20-QT < H17-QT). The reduction of residual austenite content in 20Cr2Ni4A steel and 17Cr2Ni2MoVNb steel after the cryogenic treatment process leads to an increase in
hardness. Alloying elements make the hardness of the 17Cr2Ni2MoVNb steel higher than that of the 20Cr2Ni4A steel [28].

Figure 8. Microhardness curves of experimental steel under different cryogenic treatment processes.

The wear rate histograms and friction coefficient curves of 17Cr2Ni2MoVNb and 20Cr2Ni4A steels under different processes are shown in Figure 9. It is obvious from the histogram of the wear rate that the wear rate of the samples decreased after cryogenic treatment, while the effect of the low temperature tempering on the wear rate was not very obvious. The wear rates of 17-QTCT and 17-QTC were decreased by 14.42% and 14.65%, respectively, and the wear rates of 20-QTCT and 20-QTC were decreased by 30.23% and 32.42%, respectively. From Figure 9b, it can be seen that the friction coefficient curves all went through a grinding stage at the beginning, in which the samples of 17-QT were stable after the first 5 min of grinding and then fluctuated drastically after 20 min. The friction coefficients at the stable stage were 0.82 for 17-QT, 0.65 for 17-QTCT, 0.68 for 17-QCT, 0.84 for 20-QT, 0.56 for 20-QTCT and 0.59 for 20-QCT, respectively. According to the results above, it can be seen that the wear resistance and friction stability of the samples after cryogenic treatment were improved due to the increase in martensite and the precipitation and more diffuse distribution of carbides [29,30]. Therefore, the 17-QCT shows the smallest wear rate and friction coefficient in those samples.

The morphology of worn surfaces of 17Cr2Ni2MoVNb and 20Cr2Ni4A steels through different processes are shown in Figure 10. As shown in Figure 10a–c, the dark oxidation products were formed on the surface of the wear marks of 17Cr2Ni2MoVNb steel, and some tearing occurred in the dark oxidation area on the 17-QT sample. The 17-QTCT and 17-QCT samples had very similar abrasion patterns with 17-QT and did not show significant tearing phenomena. From Figure 10d–f, it can be seen that although oxidation products were produced on the surface of the abrasion marks of the 20Cr2Ni4A steel, the substrate still underwent intense abrasive wear. The very obvious plow groove-like abrasion marks could be observed as shown in Figure 10d. A crack and the loose oxide area were observed in 20-QT and 20-QTCT samples, respectively. The fish-scale skin formed on the 20-QCT, which is the typical morphology of stress fatigue wear. According to the wear morphology, the cryogenic treatment could positively improve the wear resistance of the steel, and the wear form of 17Cr2Ni2MoVNb and 20Cr2Ni4A steels were also different. The abrasive wear occurs in the grinding process between the friction pair and the matrix material. When the friction pair is embedded in the matrix material, the carbide inside the
matrix material will peel off, and the peeled carbide will act as hard particles and damage the surface of the matrix. The morphology of abrasive wear showed obvious ravine shape. The oxidative wear is due to the heat generated between the friction pair and the matrix during the friction and wear process, and the collective surface metal reacts with oxygen in the air to form oxides. Since the friction time is 30 min, the oxides produced during the friction movement continue to peel off and slide on the surface of the substrate with the movement of the friction pair, causing adhesive wear on the substrate. The oxygen content is significantly higher than that of the matrix. [31,32] The friction form of 17Cr2Ni2MoVNb steel was mainly of oxidation wear and abrasive wear, while 20Cr2Ni4A steel contained severe adhesive wear, abrasive wear, oxidation wear and a small amount of stress fatigue wear [33–37].

Figure 9. Histogram of wear rate and friction coefficient of the experimental steel under different cryogenic treatment processes: (a) histogram of wear rate, (b) friction coefficient.

Figure 10. SEM images of samples’ grinding crack: (a) 17-QT, (b) 17-QTCT, (c) 17-QCT, (d) 20-QT, (e) 20-QTCT, (f) 20-QCT.

3.3. Effect of Cryogenic Treatment on Distortion of Navy C-Ring Samples

Figure 11 shows the gap distance of the C-ring specimens at each stage of the processes, the gap distance change $\Delta d$ after the cryogenic process and the distortion schematic diagram. As can be seen from Figure 11a, the gap distance of the steels during the quenching, tempering and cryogenic treatment process underwent shrinkage followed by expansion, with a sharp decrease and a slow increase in the processes. In these processes, the distortion mainly occurred in the quenching stage, and the distortion during cryogenic treatment and tempering was very small. Austenite has a fcc structure with a unit cell containing 4 atoms,
while ferrite has a bcc structure with a unit cell containing 2 atoms. When austenite is transformed into ferrite, a unit cell becomes two cells, resulting in volume expansion. Martensite is a supersaturated solid solution formed by carbon in ferrite. The maximum solubility of carbon in ferrite is 0.0218% at 727 °C, and the maximum solubility of carbon in austenite is 2.11%. When austenite is transformed into martensite, the crystal lattice dissolves the insoluble carbon, which “supports” the ferrite lattice to a square structure. The degree of “support” is called squareness. Therefore, the volume has also expanded. Based on the above reasons, the transformation of austenite to martensite is a volume expansion process. During the heat treatment process, the solid volume expands, resulting in the generation of internal stress. If the internal stress exceeds the yield strength of the steel, it will be deformed. Internal stresses in steel can lead to cracking and also inhibit the transformation of austenite to martensite [38,39]. The distortion schematic diagram is shown in Figure 11b, where the original shape of Nary C-rings was marked as 1 and the final one was marked as 2. It indicated that the shape of the Navy C-ring specimens also changed after heat treatment and cryogenic treatment. Due to the difference in the cooling rate of Navy-rings sample at the different position, the martensitic transformation takes place at different times. The martensite transformation occurs first at the gap and last at the core region. The distortion of the 20Cr2Ni4A steel was bigger than that of 17Cr2Ni2MoVNb steel during quenching, while the distortion of the 20Cr2Ni4A steel was slightly smaller than that of 17Cr2Ni2MoVNb steel after cryogenic treatment and tempering as shown in Figure 11a.

![Figure 11.](image_url)

**Figure 11.** (a) The notch size variation of the Navy C-ring specimen at each stage of the cryogenic process. (b) The deformation schematic diagram in initial (1) and final gap (2).

### 4. Conclusions

In this paper, the relationship between the microstructure, hardness, frictional wear and distortion of two heavy-duty gear steels after cryogenic treatment has been studied and compared. The conclusions can be drawn as follows:

1. The 17Cr2Ni2MoVNb and 20Cr2Ni4A steels had similar microstructures after carburizing, which are composed of high-carbon needle-like martensite, carbides and retained austenite in the case and low-carbon lathe martensite in the core matrix. The depth of the carburized layer was about 1.4 (±0.05) mm.

2. The volume percentages of carbides obtained by the area percentage calculation of Image-pro software are 7.36% for 17-QT, 10.36% for 17-QTCT, 12.75% for 17-QCT, 6.17% for 20-QT, 9.2% for 20-QTCT, and 11.8% for 20-QCT.

3. The cryogenic treatment effectively decreased the retained austenite content, which was decreased from 13.1 to 9.5% (QTCT) and 9.6% (QCT) for 20Cr2Ni4A steel and from 19.23 to 10.7% (QTCT) and 9.15% (QCT) for 17Cr2Ni2MoVNb steel.
(4) The hardness of the samples near the surface after cryogenic treatment was increased by 102 HV for 17-QTCT and by 122 HV for 17-QCT compared with 17-QT, and it was increased by 13 HV for 20-QTCT and by 34 HV for 20-QCT compared with 20-QT.

(5) The cryogenic treatment could effectively improve the wear resistance, and the wear rates of 17-QTCT and 17-QCT were decreased by 14.42% and 14.65%, respectively, and the wear rates of 20-QTCT and 20-QCT were decreased by 30.23% and 32.42%, respectively. The low temperature tempering sequence (QCT) in the cryogenic process had no effect on the wear resistance. The wear form of 17Cr2Ni2MoVNb steel was mainly composed of oxidation wear and adhesive wear, while the wear form of 20Cr2Ni4A steel was mainly composed of severe adhesive wear, abrasive wear, oxidation wear and a small amount of stress fatigue wear.

(6) The distortion of the two experimental steels during the heat treatment and cryogenic treatment underwent shrinkage before expansion, and the distortion of 17Cr2Ni2MoVNb steel was smaller than that of 20Cr2Ni4A steel after heat treatment and cryogenic treatment.

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