Study on the Process of Vacuum Low Pressure Carburizing and High Pressure Gas Quenching for Carburizing Steels

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Abstract. The vacuum low pressure carburizing and high pressure gas quenching processes of 20CrMo, 20CrMnTi and 20Cr2Ni4 with acetylene as carburizing medium were investigated. The results show that the carburizing and diffusion time significantly affected the carburizing performance. Carburized with the process of C2H2 flow rate 10L/min, N2 flow rate 10L/min, carburizing pressure 3kPa, carburizing time 42min, diffusion time 140min and gas quenching pressure 1.5MPa, 20CrMo, 20CrMnTi and 20Cr2Ni4 can obtain the surface carbon content of 0.74%-0.78% and carburizing depth of 0.81mm-0.83mm. Meanwhile, the microstructure showed first grade carbide, and there was no internal oxidation layer on the surface. The carburizing constant and the diffusion time to carburizing time ratio were modified to be more suitable for the carburizing process.

Keywords: Carburizing steels; Vacuum carburizing; High pressure gas quenching; Carbon content; Hardness.

1. Introduction
Carburizing is a conventional surface heat treatment process, which is widely used in various fields. In the 1920s, the United States began to use rotary hearth furnace for gas carburizing. In 1930s, continuous gas carburizing furnace began to be applied in industry. Gas carburizing at high temperature (1233-1373 K) was developed in 1960s. In the 1970s, vacuum carburizing appeared[1-3]. In the early stage of carburizing process, solid carburizing medium was used. Liquid and gas carburizing appeared in the 20th century and was widely used.

Compared with other carburizing methods, vacuum carburizing has obvious advantages [4]:
1. The surface quality of vacuum carburizing is better, no oxidation and no decarburization;
2. The deformation of the vacuum carburized parts is small, which can reduce the later processing and save the cost;
3. The depth of carburizing layer is more uniform and the carburizing quality is stable;
4. The surface carbon content is easy to control;
5. High temperature carburizing can be carried out to improve production efficiency;
6. For parts with blind holes, deep holes and slits, ordinary gas carburizing effect is not good or even difficult to carburize, while vacuum carburizing can obtain good carburizing layer;
7. Low energy consumption and environmental pollution.

In view of the above advantages of vacuum carburizing, it has attracted much attention since the appearance of vacuum carburizing process.
At present, acetylene is an ideal gas carburizing medium [5-8]. In this paper, the carburizing processes of 20CrMo, 20CrMnTi and 20Cr2Ni4 with acetylene as carburizing medium were studied, and the influence of key process parameters on carburizing performance was analyzed.

2. Experimental Procedure
In this paper, 20CrMo, 20CrMnTi and 20Cr2Ni4 were tested for vacuum low-pressure carburizing and high-pressure gas quenching, and the material compositions were shown in Table 1. The process test was carried out on the WZD-40 vacuum carburizing gas quenching multi-functional furnace in the cleaning heat treatment center of Beijing Research Institute of Mechanical and Electrical Technology Co., Ltd., the effective size of the furnace was $600 \times 400 \times 400 \text{ mm}^3$, the limit pressure of the gas quenching was 1.5MPa, and the size of the carburizing specimen was $\varnothing 15 \times 20 \text{ mm}^3$, hanging in the center of the furnace. The process tests were shown in Figure 1 and Table 2. The processes were divided into the following stages: preheating $\rightarrow$ heating and heat preservation $\rightarrow$ carburization $\rightarrow$ diffusion $\rightarrow$ cooling and heat preservation $\rightarrow$ high pressure gas quenching. According to the key parameters of acetylene ($\text{C}_2\text{H}_2$) flow rate, nitrogen ($\text{N}_2$) flow rate, carburizing pressure, carburization time, diffusion time and gas quenching pressure, the tests were conducted in 5 furnaces, as shown in Table 2.

| Materials | C  | Si  | Mn  | Cr  | Mo  | Ti | Ni  | Fe  |
|-----------|----|-----|-----|-----|-----|----|-----|-----|
| 20CrMo    | 0.22 | 0.27 | 0.47 | 0.91 | 0.17 | /  | /   | Balance |
| 20CrMnTi  | 0.20 | 0.25 | 0.74 | 0.99 | /   | 0.05 | /   | Balance |
| 20Cr2Ni4  | 0.20 | 0.43 | 0.43 | 1.44 | /   | /   | 3.40 | Balance |

**Table 1. Chemical composition of 20CrMo, 20CrMnTi and 20Cr2Ni4 steels (wt. %).**

![Figure 1. Carburizing process diagram.](image1.png)

| Process number | $\text{C}_2\text{H}_2$ flow rate(L/min) | $\text{N}_2$ flow rate(L/min) | Carburizing time(min) | $\text{C}_2\text{H}_2$ diffusion time(min) | Carburizing pressure(kPa) | Gas quenching pressure(MPa) |
|----------------|--------------------------------------|-------------------------------|-----------------------|-------------------------------------------|--------------------------|-----------------------------|
| L1             | 8                                     | 10                            | 74                    | 108                                       | 3                        | 0.5                         |
| L2             | 10                                    | 10                            | 74                    | 108                                       | 3                        | 0.8                         |
| L3             | 10                                    | 10                            | 74                    | 108                                       | 4                        | 0.8                         |
| L4             | 10                                    | 10                            | 46                    | 136                                       | 3                        | 1                           |
| L5             | 10                                    | 10                            | 42                    | 142                                       | 3                        | 1.5                         |

**Table 2. Carburizing process parameters.**
After carburizing, the cross-section of the specimens was cut. One part was used for carbon content detection. The carbon contents were measured by the infrared absorption method. The other part was used for hardness and microstructure detection. The specimens were ground, and the hardness tests were completed on micro Vickers hardness tester (INNOVATEST 423D) in the testing laboratory of Beijing Institute of Mechanical and Electrical Technology Co., Ltd. Then the specimens were etched in 4% Nitric alcohol solution, and the microstructures were examined on the optical microscope (Zeiss Axioscope. A1).

3. Results and Discussion

3.1. Influence of Carburizing Parameters on the Distribution of Carbon Content

The carbon content distribution of 20CrMo, 20CrMnTi and 20Cr2Ni4 is shown in Figure 2, Figure 3 and Figure 4. Compared with the curves of L1 and L2, the carbon content of L2 was slightly higher than that of L1, and the carburizing effect was more significant, especially for 20Cr2Ni4. The C2H2 flow rate of L1 was 8 L/min and that of L2 was 10 L/min. It can be seen that the C2H2 flow rate of L2 was large, the carbon supply capacity was better, the C2H2 content was high in the carburizing atmosphere, and the surface carburizing effect was relatively more significant. Compared with the carbon concentration distribution of L2 and L3, the carbon content of L2 with carburizing pressure 3kPa was slightly higher than L3 with carburizing pressure 4kPa, especially for 20CrMo and 20CrMnTi. Therefore, the carburizing effect with low carburizing pressure was better. Meanwhile, low pressure carburizing could reduce the carbon black and ensure the carburizing uniformity. On the premise of ensuring the carbon supply capacity, the carburizing pressure should be lower. Therefore, the C2H2 flow rate and carburizing pressure selected in process L2 were better.

Figure 2. Carbon concentration distribution with process L1, L2 and L3 of 20CrMo.

Figure 3. Carbon concentration distribution with process L1, L2 and L3 of 20CrMnTi.
Carburizing time and diffusion time significantly affected the carbon concentration distribution, as shown in Figure 5, Figure 6 and Figure 7. Both C2H2 and N2 flow rate were 10L/min, the carburizing pressure was 3kPa, and the total carburizing and diffusion time was 182min. The carburizing time and the diffusion time of L2 were 74min and 108min respectively. A lot of carbon black existed in the furnace. The surface carbon concentration was affected by some carbon black as high as 1.16% - 1.21%. The carbon concentration in the carburizing atmosphere was excessive. The total time was the same, the carburizing time of L4 was reduced to 46min, and the diffusion time was increased to 136min. The carbon black in the furnace was significantly reduced, the surface carbon concentration was reduced to 0.9% - 0.95%, and the surface carbon concentration transition was gentle. Thus, the carbon black influence was obviously reduced; meanwhile the carburizing efficiency and C2H2 utilization rate were apparently improved. The carburizing time of L5 was reduced to 42min and the diffusion time was increased to 142min, the surface carbon concentration was 0.74% - 0.78%, which reached the ideal value. There was no carbon black in the furnace, and the surface of the sample kept the original finish. It can be seen that long-time carburizing resulted in excess carbon concentration in the furnace, serious carbon black in the furnace, obvious reduction of C2H2 utilization rate. By shortening carburizing time, carbon black can be reduced, the utilization of acetylene can be increased, and the surface finish of specimen can be improved. For 20CrMo, 20CrMnTi and 20Cr2Ni4, carburizing time 42min, diffusion time 142min in this paper, ideal surface carbon content and surface quality can be obtained.
3.2. Carburizing Hardness and Microstructure Characteristics

Carburizing process L5 can obtain ideal surface carbon concentration and surface quality of test piece. The gas quenching pressure of this process was 1.5MPa, which was the upper limit gas quenching pressure of carburizing furnace and can reflect the best carburizing effect under the process. The hardness distribution is shown in Figure 8. Since the substrate hardness of 20Cr2Ni4 was 476.3HV (>450HV), the limit hardness value of hardened layer was increased to 575HV according to the provisions of GB/T 9450-2005. The substrate hardness of 20CrMo and 20CrMnTi was less than 450HV, so the limit hardness value was still 550HV. With carburizing process L5, the depths of the hardened layer of 20CrMo, 20CrMnTi and 20Cr2Ni4 were 0.81mm, 0.83mm and 0.81mm respectively, and the ideal hardened layer depths were obtained. Moreover, the hardness of the material transited smoothly from the surface to the substrate of the specimens.

Low temperature annealing heat treatment was carried out for carburizing process L5, and the structure is shown in Figure 9. There was no oxidation phenomenon in the surface layer of the three materials, and the carbides was grading 1. Therefore, the process L5 can obtain ideal microstructure.
3.3. Key Parameter of Carburizing Model

The carburizing parameters in this paper were got according to the experimental equations (Eq. 1, Eq. 2 and Eq. 3), and these equations were obtained by F.E. Harris according to Fic law[4].

\[ D = K \sqrt{T} \quad (1) \]
\[ T = T_c + T_d \quad (2) \]
\[ R = \frac{T_d}{T_c} \quad (3) \]

In the Eq. 1, Eq. 2 and Eq. 3: D carburizing depth (mm), K carburizing constant, R diffusion time to carburizing time ratio, Tc carburizing time (min) andTd diffusion time (min). The initial selection of R value and K value was referred to [4]. In this paper, the ideal carburizing depths of 20CrMo, 20CrMnTi
and 20Cr2Ni4 were 0.75-0.85mm and the surface carbon contents were 0.7% - 0.8%. The ideal surface carbon content (0.74% - 0.78%) and carburizing depth (0.81mm-0.83mm) were obtained by process L5, in which process K and R were 0.46 and 3.3 respectively. According to the hardness and carbon concentration distribution curve of process L5 in Figure 10, when the hardnesses of 20CrMo and 20CrMnTi were 550HV, the carbon concentrations were 0.57%; when the hardness of 20Cr2Ni4 was 575HV, the carbon concentration was 0.55%. Considering three kinds of materials, the limit hardness of the hardened layer was modified to 0.56%. Therefore, K was modified to 0.46 carbon concentration of 0.56%, as shown in Table 3. Meanwhile R, the depth of the effective hardening layer and the surface carbon content were modified to 3.3, 0.82mm and 0.76%. The results provided an important basis for the selection of subsequent vacuum low pressure carburizing and high pressure gas quenching process.

![Figure 10. Hardness and carbon concentration distribution with process L5.](image)

### Table 3. Key parameters of carburizing model.

| Materials   | Hardness of substrate HV0.1 | Hardness limit value HV0.1 | Carburizing temperature | Effective hardening layer depth(mm) | Surface carbon content | K (carbon content to 0.56%) | R  |
|-------------|----------------------------|---------------------------|-------------------------|-------------------------------------|------------------------|-----------------------------|----|
| 20CrMo      | 292.5                      | 550                       | 1203K                   | 0.82                                | 0.76%                  | 0.46                        | 3.3|
| 20CrMnTi    | 308.9                      | 550                       |                         |                                     |                        |                             |    |
| 20Cr2Ni4    | 476.3                      | 575                       |                         |                                     |                        |                             |    |

### 4. Conclusions

The carburizing process of 20CrMo, 20CrMnTi and 20Cr2Ni4 with acetylene as carburizing medium was investigated. The main results are as follows:

1. The carburizing parameters such as C₃H₂ flow rate, N₂ flow rate, carburizing pressure, carburizing time, diffusion time and gas quenching pressure significantly affected carburizing performance, especially carburizing and diffusion time. Long time carburizing resulted in serious carbon concentration excess and carbon black.

2. Carburized with the process of C₃H₂ flow rate 10L/min, N₂ flow rate 10L/min, carburizing pressure 3kPa, carburizing time 42min, diffusion time 140min and gas quenching pressure 1.5MPa, 20CrMo, 20CrMnTi and 20Cr2Ni4 can obtain the ideal surface carbon content (0.74% - 0.78%) and carburizing depth (0.81mm-0.83mm). Meanwhile, the microstructure showed first grade carbide, and there was no internal oxidation layer on the surface.

3. In the experimental equations obtained by F.E. Harris according to Fic law, the carburizing constant and the diffusion time to carburizing time ratio were modified to be more suitable for the carburizing process in this paper, which provided reference for the selection of subsequent test process.
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