The influence of carburization technology on performance properties of high-loaded gear wheels

S A Pakhomova, R S Fakhurtdinov, O A Tsinkolenko, B S Zolotov
Bauman Moscow State Technical University, Russia, 105005 Moscow, 2-d Bauman St., 5
mgtu2013@yandex.ru

Abstract. The purpose of the study is to develop a technology for vacuum carburization of heat-resistant steels, taking into account the requirements for the structure of the carburised layer to ensure the operational properties of gears. The paper describes the issues of improving the operating characteristic of heavily loaded gears made of high-strength steels. Information on the modes of vacuum cementation is given. A technological process has been developed that ensures the presence of carbides on the tooth profiles, the absence of a carbide mesh in the cemented layer and the optimal mechanical properties of the gears. Recommendations on the choice of modes of diffusion saturation to ensure wear resistance, contact endurance, bending strength of gears made of heat-resistant steels are proposed.

1. Introduction
Most gears of gas turbine engines operate under high contact stresses, sliding speeds, temperature influences [1, 2]. These factors lead to high requirements for the quality of hardening of gears. The implementation of such requirements necessitates the use of carburased heat-resistant complex-alloyed steels C0.20Cr3MoWV, C0.16Cr3NiWVMoNb, 0.16Cr2Ni3MoVNbAl [1, 3]. The feature of the chemical composition of heat-resistant steels is the presence of active carbide-forming elements (Cr, Mo, W, V, Nb). The consequence of this feature is the formation in the near-surface part of the carburased layer of carbide phase particles – alloyed cementite Fe(Cr, Mn)3C and special carbides: Me7C3, Me23C6, VC and NbC. The formation of a high-carbon carbide phase is accompanied by a carbon concentration decrease in the martensite (structural basis of the layer) and as a consequence of its hardness to 700...740 HV (58...59 HRC), which is lower than the required (60...63 HRC) values. Therefore, the surface structure with a certain proportion of the carbide phase is optimal and capable of providing the required working capacity of gears [1].

The formation of the carbide phase requires a high saturating capacity of the process atmosphere. This ability has a gas medium of acetylene, used in vacuum carburization. Carburization in low-pressure acetylene is a new process that has been widely used. The authors [4, 5] called vacuum carburization in acetylene the latest achievement in the development of carburization technology. For its implementation, vacuum automated installations are produced, providing diffusion saturation with carbon and subsequent low-deformation "dry" quenching in the nitrogen stream [6].

The purpose of the work is to develop a technology for vacuum carburization of heat-resistant steels, taking into account the requirements for the structure of the cemented layer to ensure the operational properties of gears.

2. Materials and equipment of the experiment
Vacuum carburization was carried out on a pilot installation, equipped with a control computer and automatic control systems for technological parameters [7, 8]. Acetylene was fed into working chamber cyclically. That is, by alternating the active stages, when the carburization gas was supplied to the working chamber, and the passive (diffusion) stages when the gas medium was switched off. The subject of the study were samples Ø50 mm · 20 mm of steel C0.16Cr3NiWVMoNb. Carburased samples were used to study the structure of the carburased layer, the distribution of carbon concentration and hardness. Metallographic studies were performed for two states: 1) after a diffusion saturation and high tempering at a temperature of 650 °C, 5 hr; 2) after a full cycle of hardening heat treatment.

The result of carburization was estimated by concentration curves obtained by layer-by-layer analysis performed by the spectral method. The carbon saturation of the layer was estimated by the effective thickness ($h_{ef}$), as the most saturated ($C \geq 0.4 \%$) part of the layer), the carbon concentration on the surface ($C_s$) and at a distance of 0.2 mm from the surface ($C_{0.2}$) after removal of the 0.2 mm allowance by grinding. The effective layer thickness was determined metallographically by the structure after diffusion saturation and high tempering, as the distance from the sample surface to half of the transition zone.

3. Experimental results and discussion

To develop of vacuum carburization technology, it is important to understand the mechanism of formation of the carburased layer. As shown in previous studies [7, 9], the carburased layer is formed as a result of intensive catalytic decomposition of acetylene molecules on the metal surface. In this case, an intensive transfer of carbon from the gas medium to the saturated surface is realized. During the active phase of the cycle, the surface of the heat-resistant steel is covered with an almost continuous layer of carbides. According to metallographic and micro-x-ray spectral analyses, such a layer is formed by thin flat carbides of alloyed cementite [7, 10]. At the passive (diffusion) stage of the cycle, a significant portion of these carbides dissolve, supplying carbon atoms to the solid solution. From cycle to cycle these processes are repeated.

Vacuum carburization is a multifactorial process. For its carrying out the technological factors expedient to divide into two groups: 1) conditionally constant factors (temperature of process, the expense of acetylene, the pressure - supported in the course of saturation at a constant level); 2) controlling factors (time of diffusion saturation and a mode of cyclic giving of acetylene).

3.1. Influence of constant factors

Temperature is an important technological factor determining the rate of diffusion saturation. The range of temperature selection is quite wide: from 880 to 980 °C. When the temperature increases, the duration of the process is significantly reduced, but the structure of the carbide zone changes: carbide particles are enlarged, their number per unit area decreases, the proportion of the carbide phase decreases. For vacuum carburization of heat-resistant steels, a temperature of 940 °C is appropriate, which provides, along with a high rate of diffusion saturation, fine carbide particles.

The expense of acetylene should be sufficient to ensure the desired saturation of the carburased layer. It is determined approximately on the basis of a simple calculation [11]. The pressure in the range of values 4...15 gPa accepted in practice practically does not influence on the characteristics of the layer [12, 13]. The expense of acetylene, as well as the pressure value, are controlled factors. During the experiments, their values were: the expense of acetylene – $6 \times 10^3 m^3/hr$, pressure – 8 gPa.

3.2. Influence of controlling factors

Control factors, which include: a) the total saturation time $\tau$; b) the time mode of acetylene supply, which is characterized by a large group of parameters (the structure of the cycle in the form of combinations of times of stages $\Sigma \tau_a$ and $\Sigma \tau_d$; the total time of active stages of cycles $\Sigma \tau_a$, the total time of diffusion stages of cycles $\Sigma \tau_d$ and their ratio $\Sigma \tau_a : \Sigma \tau_d$, the total number of cycles $n$ during saturation $\tau$).

3.2.1. The influence of the total time of carburization. The time of diffusion exposure determines the
effective thickness of the diffusion layer and the length of the carbide zone. The kinetics of the diffusion layer is subject to a parabolic dependence: \( h_{ef} = k \cdot \sqrt{\tau} \), where \( k \) is the kinetic coefficient. It is experimentally established that for heat-resistant steels \( k = 0.46 \). The total time of diffusion saturation for the main groups of gears used in aircraft engines is presented in Table 1 (where \( \tau = (h_{ef}/k^2) \)).

Table 1. Estimated time for carburization at \( t = 940 \, ^\circ \text{C} \) for the main groups of gears

| № groups | The effective thickness \( h_{ef}, \text{mm} \) before grinding | The effective thickness \( h_{ef}, \text{mm} \) after grinding | The time of carburization \( t, \text{hr} \) |
|-----------|-------------------------------------------------------------|-----------------------------------------------------|-------------------------------------|
| 1         | 0.7…0.9                                                    | 0.5…0.7                                             | 2.4                                 |
| 2         | 0.9…1.1                                                    | 0.7…0.9                                             | 5.1                                 |
| 3         | 1.1…1.3                                                    | 0.9…1.1                                             | 6.8                                 |
| 4         | 1.3…1.5                                                    | 1.1…1.3                                             | 9.3                                 |

The combination of the time cyclic parameter determines many treatment options. Two schemes of cyclic mode of acetylene supply were used for diffusion saturation: 1) simple or periodic \( n \cdot (\tau_a / \tau_d) \), for example, 20 \cdot (5/10); 2) complex or aperiodic \( n_1 \cdot (\tau_{a1} / \tau_{d1}) + n_2 \cdot (\tau_{a2} / \tau_{d2}) \), for example, 8 \cdot (13/17) + 2 \cdot (9/21).

3.2.2. Carburization results in the simple scheme of the cyclic mode. Influence of total time of active saturation stages \( \Sigma \tau_a \). The total time of the saturation stages \( \Sigma \tau_a \) and, as a consequence, the ratio of the duration of the stages depends on the flow of carbon into the surface layer. Therefore, this time factor serves as an important tool for controlling the layer saturation, thickness and structure of the carbide zone. As an example, the results of metallographic studies performed at the total saturation time \( \tau = 300 \, \text{min} \), the constant time of the active stage of the cycle \( \tau_a = 2 \, \text{min} \) and the different time of the passive stage \( \tau_d = 20, 10, 6, 4, \) and \( 2 \, \text{min} \) are presented below. The latter corresponds to the duration of the cycles stages ratio \( \Sigma \tau_a : \Sigma \tau_d = 0.1; 0.2; 0.3; 0.5; 1.0 \) (Table 2).

Table 2. The influence of the time parameters \( \Sigma \tau_a \) and \( \Sigma \tau_d : \Sigma \tau_d \) on the carburased layer characteristics

| The time of the active stage, \( \Sigma \tau_a, \text{min} \) | The ratio of the cycles stages, \( \Sigma \tau_a : \Sigma \tau_d \) | The number of cycles, \( n \) | The effective thickness \( h_{ef}, \text{mm} \) | The thickness of the carbide zone \( h_{car}, \text{mm} \) |
|-----------------------------------------------|-------------------------------------------------|-----------------|-----------------|-----------------|
| 28                                           | 0.1 (1:10)                                     | 14              | 1.05            | 0.10            |
| 50                                           | 0.2 (1:5)                                      | 25              | 1.05            | 0.14            |
| 75                                           | 0.3 (1:3)                                      | 38              | 1.10            | 0.20            |
| 100                                          | 0.5 (1:2)                                      | 50              | 1.10            | 0.29            |
| 150                                          | 1.0 (1:1)                                      | 75              | 1.15            | 0.35            |

It follows from the table that the effective layer thickness practically does not depend on the parameter \( \Sigma \tau_a \). The thickness of the carbide zone \( h_{car} \) increases in proportion to the time of the active stages \( \Sigma \tau_a \) and the ratio of the stages times \( \Sigma \tau_a : \Sigma \tau_d \) from 0.1 to 1.0. The difference in the microstructure of the carburased layer is seen in figure 1.
The results of the carbide zone particles quantitative analysis confirm that the volume fraction of the carbide phase particles increases significantly with increasing the ratio $\Sigma \tau_a : \Sigma \tau_d$ from 0.1 to 0.3 (figure 2). In accordance with the distribution of the carbide phase changes the concentration of carbon $V_{car}$ in the carburased layer thickness $h$ (figure 3). The concentration of carbon on the surface (measured at a distance of 0.05 mm) increases, and at a distance of 0.2 mm from the surface less intense (figure 4).

Figure 1. Microstructure of the near-surface layer of samples saturated with different ratio of cycle stages duration (shown below the figure)

Figure 2. Distribution of the volume fraction of the carbide phase particles $V_{car}$ over the thickness of the diffusion layer $h$ at different ratio of cycle stages duration $\Sigma \tau_a : \Sigma \tau_d$ (shown on the curves)
Figure 3. Distribution of the carbon concentration $C$ over the thickness of the diffusion layer $h$ at different ratio of the duration of cycle stages $\Sigma \tau_{a}: \Sigma \tau_{d}$ (shown on the curves)

Figure 4. Changes in the carbon concentration of $C_s$ and $C_{0.2}$ in depending on the ratio of the duration of cycle stages $\Sigma \tau_{a}: \Sigma \tau_{d}$

3.2.3. Influence of the number of cycles. If the total process time $\tau$ is constant, the number of cycles $n$ can be increased only by reducing the cycle time: $\tau_{a} + \tau_{d}$. The effect of the number of cycles by reducing the time of the passive stage is equivalent to an increase in the time of the active stages $\Sigma \tau_{a}$ and the ratio of the duration of the stages $\Sigma \tau_{a}: \Sigma \tau_{d}$. The influence of these parameters is discussed above and reflected in the table 2. It follows from it that the reduction of the time of passive stages $\tau_{d}$ from 20 to 2 min at a constant total saturation time of 300 min is accompanied by an increase in the number of cycles from 14 to 75 and a noticeable increase in the thickness of the carbide zone. Its growth indicates the dominant role of the surface layer of carbides in the transfer of carbon from the gas medium to the saturated surface. The layer carbon saturation increases due to the fact that the proportion of the surface not covered with carbides decreases.

A similar result was obtained in a series of experiments in which an increase in the number of
cycles was achieved by reducing the time of both the active $\tau_a$ and diffusion $\tau_d$ stages (figure 5).

![Graph](image)

**Figure 5.** Dependence of carbon concentration $C_s$ (a) and $C_{0.2}$ (b) by the number of saturation cycles ($t = 940 ^\circ C$; $t = 300 \text{ min}$; $\Sigma \tau_a = 66 \text{ min}$; $\Sigma \tau_d = 242 \text{ min}$)

From figure 5 it follows that the most noticeable increase in the carbon concentration on the surface and the thickness of the carbide zone occurs when the number of cycles increases to 30. It is likely that with too many cycles there will be a lack of time required for the carbide phase to dissolve more completely on the surface.

3.2.4. **Results of carburization in complex schemes of acetylene supply.** Along with complex cyclic schemes (№2; №3; №4), simple schemes (№1 and №5) were studied (table 3). In the formation of complex schemes, the total number of cycles $n$ was divided into 2 or 3 groups of cycles. In these groups, both the number of cycles and the duration of the stages varied. At the same time, the total number of cycles and the time of active stages $\Sigma \tau_a$ was the same for all cyclic schemes.

| № | The cyclic schemes | The number of cycles, $n$ | The time of active stages, $\Sigma \tau_a$, $\min$ | The effective thickness of the carbide phase, $h_{ef}$, $\text{mm}$ | The thickness of the carbide zone, $h_{car}$, $\text{mm}$ | The amount of carbide phase, $V_{car}$, % | $C_s$, % |
|---|-------------------|--------------------------|---------------------------------|--------------------------|--------------------------|-------------------------------|--------|
| 1 | $25 \cdot (2/10)$ | 25                       | 105 ± 10                        | 0.23 ± 0.2               | 21 ± 2                   | 1.93 ± 2                         | 2.14   |
| 2 | $18 \cdot (2/6) + 7 \cdot (2/20)$ |                     |                                |                          |                          |                                |        |
| 3 | $15 \cdot (2/7) + 6 \cdot (2/10) + 4 \cdot (2/20)$ | 25                       | 1.10                           | 0.23 ± 0.2               | 21 ± 2                   | 1.93 ± 2                         | 2.14   |
| 4 | $12 \cdot (2/5) + 7 \cdot (2/10) + 6 \cdot (2/20)$ |                     |                                |                          |                          |                                |        |
| 5 | $10 \cdot (5/25)$ | 10                       |                                |                          |                          |                                |        |

From the data of the table it follows that the change of the cycles schemes at constant time of active stages $\Sigma \tau_a$ has a weak influence on the characteristics of the layer. However, it should be considered preferable to complex cycles containing from 2 to 3 last cycles with an increased diffusion stage to eliminate the supersaturation of the surface with carbon. The purpose of the first group of cycles is to provide active carburization of the surface; the second and third groups-to create a condition for more intensive diffusion removal of carbon from the surface.
Sufficient cyclic strength is an important condition for the efficiency of gears. For heat-resistant steels according to [14, 15], the greatest value of the tooth strength during bending is achieved at a carbon concentration on the surface of 0.9...1.0 % and a layer thickness of 0.7...0.9 mm. To ensure such characteristics of the diffusion layers, a carbide zone with small and rare carbide particles is required. The density of the hardening phase should be to the extent that it, increasing the volume changes of the surface layer, contribute to the formation of high residual compression stresses in it.

Conclusions
1. The formation of an optimal structure with small and rare carbide particles is provided by cyclic regimes with an increased diffusion stage time and the ratio of stages $\Sigma \tau_a : \Sigma \tau_d$ equal to 0.1...0.2. These include: $8 \cdot (4/26) + 2 \cdot (3/27)$ and $7 \cdot (5/25) + 3 \cdot (2/28)$.
2. When vacuum carburization is possible a wide range of changes in the characteristics of the diffusion layer—its saturation, hardness, structural and phase composition, which makes it possible to provide at the required level of the performance property, which is decisive for this type of gear.
3. The established regularities can be used to control the thickness and structure of the carbide zone of the carburized layer, taking into account the requirements for the operational properties of the gears: wear resistance, contact endurance, cyclic strength.

References
[1] Eliseev Yu S, Krymov V V and Nezhurin I P 2001 Production of gear wheels of gas turbine engines (Moscow: Higher school) 493 p
[2] Alekseev V I, Ananyev V M and Bulygina M M 1981 Aviation gears and gearboxes (Moscow: Mechanical Engineering) 374 p
[3] Banas I P, Alekseeva G P and Utkina A N Modern steels for highly stressed gears 1985 (Bulletin of mechanical engineering) № 9 pp 12-15
[4] Grafen W and Edenhofer B Acetylene low-pressure carburising – a novel and superior carburizing technology 1999 (Heat treatment of metals) 26 № 4 pp 79–85
[5] Kula P, Olejnik J and Kowalewski J New vacuum carburizing technology 2001 (Heat treatment progress) 1 № 1 pp 57–65
[6] Fakhrutdinov R S, Pakhomova S A and Ryzhova M Y On the problems of modernizing equipment for vacuum carburization 2017 (Journal of Machinery Manufacture and Reliability) 46 № 2 pp 187–192, DOI: 10.3103/S1052618816060066
[7] Fakhrutdinov R S, Ryzhova M Y and Pakhomova S A Advantages and commercial application problems of vacuum carburization 2017 (Polymer Science. Series D) 10 № 1 pp 79-83, DOI: 10.1134/S1995421217010063
[8] Buzaverov K A, Gress M A, Ryzhova M Yu and Shebeshev K I Hardening heat treatment of economically alloyed steel after cementation 2019 (Bulletin of scientific and technological development) № 2 (138) pp 3-8
[9] Zinchenko V M 2001 Inzheneriya poverkhnosti zubchatykh koles metodami khimiko-termicheskoi obrabotki [The Engineering of the Surface of Gear Wheels by the Methods of Chemical Heat Treatment] (Moscow: MGTU im N E Bauman Press) 303 p
[10] Panin V E and Panin A V Fundamental role of nanoscale structural level of plastic strain in solids 2006 (Metal Science and Heat Treatment) 48 № 11–12 pp 533–538
[11] Ryzhov N M, Smirnov A E and Fakhrutdinov R S Controlling the carbon saturation of the diffusion layer during vacuum cementation of heat-resistant steels 2004 (Metal Science and Heat Treatment) № 8 pp 22-27
[12] Lakhtin Yu M and Arzamasov B N 1985 Khimiko-termicheskaya obrabotka metallov [Chemical Heat Treatment of Metals] (Moscow: Metallurgiya) 256 p
[13] Shebeshev K I, Buzaverov K A, Ryzhova M Yu and Gress M.A. Improving the contact endurance of gears made of steel C0.25Cr13Ni2 2018 (Bulletin of scientific and technological development) № 6 (130) pp 10-15
[14] Pakhomova S A, Unchikova M V and Fakhurtdinov R S Gear wheels surface engineering by deformation hardening and carburization 2016 (*Materials Science Forum*) 870 pp 383391, DOI: 10.4028/www.scientific.net/MSF.870.383

[15] Grishin V I Increasing the contact endurance of parts made of masonry steel C0.12Cr2Ni4 2016 (*Bulletin of scientific and technological development*) № 11 (111) pp 3-9