Investigation of the contact fatigue strength of high quality carburised steel

S A Pakhomova, R S Fakhurdinov, E Zhavoronkova and K Zinkovich

Bauman Moscow State Technical University, 2-d Bauman Street, 5, Russia, Moscow, 105005

mgtu2013@yandex.ru

Abstract. The parameters of contact fatigue strength during vacuum carburization and ion nitriding of high quality steel (HQS) HQS-7 and HQS-10 are considered. Information about the modes of chemical and heat treatment is given and the technological process of hardening for HQS-7 and HQS-10 steels is considered. The characteristics of the contact fatigue strength of steels in the statistical aspect at different levels of contact stresses are obtained. A graphical analysis of the obtained values after testing was carried out, the optimal stresses for research were determined and the optimal version of chemical heat treatment was selected, which determines the best indicators for mechanical characteristics and operational requirements.

1. Introduction

The gears of modern engines are subject to high power and temperature loads. They are made mainly from carburised or nitrided complex-alloyed heat-resistant steels [1, 2]. One of the main criteria for the performance of gears is the contact fatigue strength of the material. However, data on the contact fatigue strength of heat-resistant steels are fragmentary and sometimes contradictory [3–5]. Therefore, the study of the contact fatigue strength of high-loaded parts is an important task in solving the current problem of ensuring the reliability of aircraft engine gears.

The vacuum carburization process is increasingly used, especially in mass production. Vacuum carburization has a number of advantages over conventional carburization. Vacuum carburization was carried out in acetylene at a temperature of 940°C for 5 hours according to cyclic modes selected in accordance with the recommendations [6, 7]. To ensure a high limit of contact fatigue strength, the acetylene supply mode was used, which includes two groups of cycles: the first group of cycles provides active saturation of the surface with carbon, the second group – diffusion redistribution of the carbon concentration and active saturation of the near-surface zone of the layer.

The process of nitriding in a glow discharge is carried out on the final processed parts [2, 8–10]. Ion nitriding includes two stages: surface cleaning by cathode sputtering and nitriding itself, which is carried out at a temperature of 500…600°C in an atmosphere of 95% N₂ + 5% H₂. The first stage provides activation of the surface and destruction of oxide films, and the second stage – heating the surface to the diffusion temperature and saturation with nitrogen.

To increase the contact fatigue strength of gears, other methods of surface hardening are also used. For example, various methods of deformation processing are widely used [11–14]. One of the most effective methods is also electro–mechanical treatment [15–17], the combination of which with chemical heat treatment (CHT) is insufficiently studied and also the methods of laser carburization of
low-alloy tool steels [18].

The purpose of this work is to analyze the contact endurance during vacuum carburization and ion nitriding of HQS-7 and HQS-10 steels used in the manufacture of gears. For this purpose, a number of fracture tests were performed and the optimal stresses for research were determined.

2. Materials and equipment of the experiment
The objects of research made of HQS-7 and HQS-10 steels that had undergone the entire complex of chemical heat treatment, including vacuum carburization (or nitriding), quenching and tempering. The table 1 below shows the chemical composition of HQS-7 and HQS-10 steels.

Table 1. Chemical composition of the studied steels.

| Steel grade | C   | Cr  | Ni  | Mn  | W  | Si  | V  | Nb  | Al  |
|-------------|-----|-----|-----|-----|----|-----|----|-----|-----|
| HQS-7       | 0.14–0.18 | 1.8–2.2 | 2.7–3.0 | 0.4–0.6 | 0.2–0.3 | 0.17–0.3 | 0.1–0.3 | 0.1–0.2 | 0.02–0.07 |
| HQS-10      | 0.10–0.15 | 3.0–3.4 | 2.7–3.0 | 1.9–2.3 | 0.6–0.5 | 0.17–0.5 | 0.1–0.37 | 0.05–0.15 | 0.02–0.04 |

Note: no more than 0.015% of sulfur and no more than 0.025% of phosphorus.

Chemical and heat treatment was performed on SECO/WARWICK equipment [19]. For comparison, two methods of CHT were studied: vacuum carburization (VC) and ion nitriding (IN). For HQS-7 and HQS-10 steels, pre-heat treatment was performed before nitriding, which includes two operations: quenching and high tempering (table 2). This treatment provides high viscosity and strength of the part core [20, 21].

Table 2. Chemical and heat treatment of the studied steels.

| Steel grade | The chemical heat treatment mode | The surface layer structure |
|-------------|----------------------------------|----------------------------|
| HQS-7       | vacuum carburization $t = 880^\circ\text{C}$, $\tau = 5$ h; high tempering $t = 660^\circ\text{C}$, $\tau = 3$ h; quenching $t = 1010^\circ\text{C}$; cold treatment $t = -70^\circ\text{C}$, $\tau = 0.5$ h; tempering $t = 240^\circ\text{C}$, $\tau = 2$ h | fine-needlepoint martensite with inclusions of fine carbides, HR15N 89…92, the layer thickness of 3.2 mm |
| HQS-7       | quenching $t = 950^\circ\text{C}$; high tempering $t = 640^\circ\text{C}$, $\tau = 3$ h; ion nitriding $t = 650^\circ\text{C}$, $\tau = 4$ h | nitrogenous sorbitol with inclusions of fine carbonitrides, HR15N 87…89, the layer thickness of 0.5 mm |
| HQS-10      | vacuum carburization $t = 880^\circ\text{C}$, $\tau = 5$ h; high tempering $t = 660^\circ\text{C}$, $\tau = 3$ h; quenching $t = 1010^\circ\text{C}$; tempering $t = 510^\circ\text{C}$, $\tau = 3$ h; cold treatment $t = -70^\circ\text{C}$, $\tau = 0.5$ h; tempering $t = 510^\circ\text{C}$, $\tau = 2$ h | fine-needlepoint martensite with a small amount of fine carbide-inclusions, HR15N 89…92, the layer thickness of 3.0 mm |
| HQS-10      | quenching $t = 950^\circ\text{C}$; high tempering $t = 670^\circ\text{C}$, $\tau = 3$ h; ion nitriding $t = 650^\circ\text{C}$, $\tau = 4$ h | nitrogenous sorbitol with inclusions of fine carbonitrides, HR15N 87…89, the layer thickness of 0.5 mm |
Samples that were not saturated with carbon or nitrogen were subjected to typical hardening heat treatment. It included quenching \( t = 950°C \) for both steels and tempering \( (\tau = 3 \text{ h}) \) with \( t = 650°C \) and \( t = 670°C \), for HQS-7 and HQS-10, respectively.

It is known [1–3] that after carburization it is impossible to obtain the maximum hardness. Therefore, the final hardening heat treatment was carried out, combining quenching and different tempering modes. The purpose of high tempering is to give the core of the parts maximum viscosity while maintaining sufficient resilience and strength limit of the metal. In this case, the residual austenite of the surface layer decays. The purpose of quenching: a) grind the core grain to increase the viscosity required by the core; b) break the carburization grid on the surface to eliminate its brittleness; c) complete dissolution of excess phases. There is an increase in hardness. Cold treatment is conduct to ensure the decomposition of residual austenite, increase the properties (mainly hardness) and stabilize the size of parts. Last tempering to relieve residual stress. As a result of such complex processing, parts receive the necessary values of physical and mechanical properties: high hardnes, wear resistance, contact fatigue strength, etc.

Contact fatigue strength tests were realized on a modernized MKV-K installation at contact stresses \( \sigma_{Z_{\text{max}}} = 780–1020 \text{ MPa} \). The contact fatigue specimen is a roller of 30.2 mm in diameter and 18.5 mm in length. This specimen is rolled reciprocally with a fatigue tester with a slip ratio of 20 %. Tests consist of running a sample between two test disks, one of which is a drive disk and the other is a pressure disk. The speed of the drive disk is 100 s\(^{-1}\). The load on the sample is applied by means of a pressure test disc from the spring loading mechanism through a system of levers. The samples were lubricated by the drip method with synthetic oil with a complex of additives IPM–10 (TU 38.10112 99-2006).

The number of samples in one batch was 10–14 pieces to ensure high accuracy of test results. For the production of samples, rods with a diameter of 15 mm were taken from the studied steels.

Metallographic analysis of micro-glyphs was performed on a Neophot-32 light optical microscope. For the study, steel samples were made after etching in a 5 % solution of HNO\(_3\) in ethyl alcohol. Microhardness was measured on a PMT-3 device at a load of 0.1 N.

3. Experimental results and discussion

Metallographic studies have shown that the diffusion layer after vacuum carburization has a structure characteristic of the carburised layer. The microstructure and distribution of carbon across the layer are shown in figure 1. It can be seen that the near-surface layer is sufficiently saturated with carbon and contains a well-developed carbide phase.

![Figure 1. Carbon saturation (a) and microstructure of the carburised layer (b) of HQS-10 (1) and HQS-7 (2) steels after vacuum carburization.](image-url)
The main research was related to contact endurance tests. Samples which had sharply distinguished (abnormal) number of cycles were screened out. Thus, gross errors are excluded from calculations. When processing the data, we used the obtained mathematical expectation (the arithmetic mean of the observed values of a random variable, and the sample average). It is proved that if certain conditions are met, the sample average tends to the true value of the mathematical expectation of a random variable when the sample size (the number of observations, tests, measurements) tends to infinity [22].

After plotting the dependence of the number of cycles on the various stresses applied to the samples, the optimal values required for testing were found (figure 2).

\[ \text{Figure 2. Contact fatigue strength of } HQS-7 \text{ (a), (b) and } HQS-10 \text{ (c), (d) steels after vacuum carburization (a), (c) and ion nitriding (b), (d) depending on the stresses } \sigma \text{ during the test.} \]

The graphs presented are inaccurate, but they give an idea of the maximum stresses at which further testing of samples should be performed. The inaccuracy of the graphs is due to the following reasons:

- heterogeneity of the material structure (large/small grain in the area of the neck of the gap/the place of fixing the sample or Vice versa), the concentration of impurities, etc.;
- anisotropy of the sample properties that increases with the number of loading cycles;
- hardening and accumulation of dislocations (especially in the area of the neck of the rupture);
- anisotropy of the sample properties, increasing with increasing number of loading cycles;
- systematic and static measurement error;
- non-systematic errors due to insufficient number of measurements.

Analysis of the results of measurements of the contact endurance of diffusion layers allows us to conclude that the optimal operating stresses are 980 MPa for testing the contact endurance of HQS-7 and HQS-10 steels, since they are the most indicative. After testing with stresses less than \( \sigma = 940 \text{ MPa} \), a lot of samples are taken without damage, and at \( \sigma = 1020 \text{ MPa} \) — a very large
variation in the final values.

Electronographic examination of surfaces with fractures (pitting) confirmed the typical fatigue nature of the fracture. The vast majority of the resulting microcracks are located at an angle of 30…45° to the surface, and on a number of transverse microshifts made from samples, primary cracks were observed under the surface, preferably in the zone of maximum shear stresses. A comparative cartogram of the studied steels after testing for contact endurance with operating stresses $\sigma = 980$ MPa is shown in figure 3.

![Figure 3](image)

**Figure 3.** Contact endurance of HQS-7 (1–3) and HQS-10 (4–6) steels after CHT including vacuum carburization (2 and 5) or ion nitriding (3 and 6); without both of carburization and nitriding (1, 4) (tests were performed at $\sigma = 980$ MPa).

Tests have shown that after vacuum carburization, the durability of HQS-7 and HQS-10 steels is higher than after ion nitriding by about 23%, which is due to the greater length of the diffusion layer. It can be seen that both processes, such as carburization and nitriding, contribute to a significant increase in the durability of the studied steels. So, thanks to vacuum carburization, the durability becomes approximately 3.5 times more, and thanks to ion nitriding – 2 times.

In optical and electron microscopic studies, the greatest changes in the structure were observed on the run-in surface and in layers very close to the surface. As you move away from the surface, the degree of martensite distortion decreases and, starting from a depth of 30–40 $\mu$m, the structure does not differ from the original one. Figure 4 shows the distribution of microhardness and microstructure of the diffusion layer of HQS-10 steel after vacuum carburization and hardening heat treatment, which provides maximum contact fatigue strength.
Analysis of the microstructure of the carburised layer shows the following: the surface part is composed of martensite and carbides, the thickness of the carbide zone is about 0.5 mm, and the carbides are located discretely and have a favorable globular shape.

Measurement of microhardness in the depth of cross sections showed that the extended carbide zone and the dense arrangement of particles in it provides increased surface hardness and smooth distribution over the layer thickness (see figure 1 (b)).

4. Conclusions
1. It is shown that the maximum stresses during tests for contact fatigue strength of samples made of HQS-7 and HQS-10 steels should be 980 MPa.
2. It was found that samples after chemical heat treatment, including vacuum carburization, have on 23 % greater durability compared to ion nitriding.
3. Carburization and nitriding processes contribute to a significant increase in the durability of the HQS-7 and HQS-10 steels. So, due to vacuum carburization, the durability becomes approximately 3.5 times greater, and due to ion nitriding – 2 times.

References
[1] Kablov E N, Bakradze M M, Gromov V I, Voznesenskaya N M and Yakusheva N A 2020 New high-strength structural and corrosion-resistant steels for aerospace engineering developed by «VIAM» (review) Aviation materials and technologies 58 pp 3-11
[2] Suslov A G 2008 Engineering of surface parts (Moscow: Mashinostroyeniye) p 320
[3] Zinchenko V M 2001 The Engineering of the Surface of Gear Wheels by the Methods of Chemical Heat Treatment (Moscow: MGTU N E Baumana Press) p 303
[4] Fakhurdinov R S, Ryzhova M Y and Pakhomova S A 2017 Advantages and commercial application problems of vacuum carburization Polymer Science, Series D 10 pp 79-83 DOI:10.1134/S1995421217010063
[5] Silkin A A, Linnik A A, Pankratov A S, Kurganova Y A, Kobernik N V and Mikheev R S 2016 Formation of the structure of the weld metal upon the introduction of nanoparticles into the weld pool Russian metallurgy (Metally) 13 1253-6 DOI: 10.1134/S0036029516130206
[6] Fomina L P 2014 Influence of chemical heat treatment on the endurance of teeth when bending Metal Technology 1 pp 11-4
[7] Pakhomova S and Karpukhin S 2020 Technological bases for increasing the durability of aviation parts by chemical heat treatment IOP Conf. Series: Materials Sci. and Engineering 963 012006 DOI:10.1088/1757-899X/963/1/012006
[8] Semenov M Yu 2013 Management of the structure of carburization layers of heat-resistant steels Metal. Sci. and Heat Treatment 5 pp 31-8
[9] Kuksenova L I, Gerasimov S A, Alekseyeva M S and Gromov V I 2018 Influence of vacuum chemical heat treatment on wear resistance of VKS7 and VKS10 steels Aviation materials and technologies 50 pp 3-8
[10] Kula P, Olejnik J and Kowalewski J 2001 New vacuum carburizing technology Heat treatment progress 1 pp 57–65
[11] Polyakov S A, Kuksenova L I, Lapteva V G and Alekseyeva M S 2016 Analysis of microplastic deformation processes of surface layers of nitrided structural steels Inorganic Materials: Applied Research 7 (4) pp 618-23 DOI: 10.1134/S2075113316040298
[12] Fomina L P 2018 Influence of high-temperature hardening processes on the deformation of aviation engine gears Metal technology 6 pp 28-31
[13] Lashnev M M 2011 Process control of vacuum carburizing (carbonitriding) heat-resistant steels Metallurgy of Machinery Building 4 pp 45-6
[14] Pakhomova S A and Manayev O I 2018 Effect of heat shotblast treatment exerted on the contact fatigue of carburised heat-resistant steel C0.12Cr2NiWV Inorganic Materials: Applied Research 9 pp 732–5 DOI: 10.1134/S2075113318040251
[15] Morozov A, Fedotov G, Fedorova L, Musharapov D and Khabieva L 2019 The providing durability of the movable square-sided spline joints by electromechanical treatment of the working surfaces MATEC WEB of Conf. ICMTMTE 2019 298 00117 DOI:10.1051/matecconf/201929800117
[16] Fedorova L, Fedorov S, Sadovnikov A, Ivanova Y and Voronina M 2018 Abrasive wear of hilong botn hardfacings IOP Conf. Series: Materials Sci. and Engineering 307 012038 DOI: 10.1088/1757-899X/307/1/012038
[17] Fedorova L V, Fedorov S K, Ivanova Y S and Voronina M V 2017 Increase of wear resistance of the drill pipe thread connection by electromechanical surface hardening International J. of Applied Engineering Research 18 7485-9
[18] Marinin E A, Chirkov A M, Gavrilov G N, Fetisov G P, Chernyshov D A and Kurganova Yu A 2018 Experimental evaluation of the methods of laser cementation of low-alloy tool steels Russian metallurgy (Metalloved.) 13 pp 73-7 DOI: 10.1134/S0036029518130153
[19] Fakhurtdinov R S, Pakhomova S A and Ryzhova M Y 2017 On the problems of modernizing equipment for vacuum carburization J. of Machinery Manufacture and Reliability 46 (2) pp 187–92 DOI: 10.3103/S1052618816060066
[20] Kuksenova L I, Polyakov S A, Lapteva V G and Alekseyeva M S 2015 Mechanical properties of surface layers of structural steels after nitriding and possibilities of adaptation of their nanostructure to contact deformation Metal. Sci. and Heat Treatment 57 (7-8) pp 436-42 DOI: 10.1007/s11041-015-9901-7
[21] Kalashnikov A S, Morganov Yu A and Kalashnikov P A 2018 Advantages of gas vacuum carburization and gas quenching under high pressure in processing a hypoid gear of the shaft type Handbook Engineering journal 8 pp 3-7 DOI: 10.14489/hb.2018.08.pp.003-007
[22] Livshits M Yu, Derevyavan M Yu and Yakubovich E A 2017 Optimal control of an object with distributed parameters on the example of vacuum carburization Mathematical methods in engineering and technology 12 pp 24-30