Effect of heat treatment conditions on structure and properties of high-speed steel

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Abstract. High-speed steels made by powder and traditional metallurgical technology have been investigated. These steels are used for manufacturing of metalworking tools. Powder high-speed steels have a large safety margin and a high level of mechanical properties. Mechanical properties and the structure of steels S390 MICROCLEAN® and Fe-9%W-4%Mo-8%Co were compared after their hardening heat treatment. The composition of the carbides was determined by x-ray phase analysis. Residual stresses of the finished cutters were determined. It was shown that the mechanical properties of steels have been determined by the phase composition and the degree of carbides dispersion. The dependence of the microstructure and the high-speed steels phase composition on heat treatment conditions was identified. The conclusion about structure control effectiveness in the adjustment of heat treatment conditions of high speed steels was made.

1. Introduction

The metal cutting is an important method of components obtaining in aircraft engineering. In many publications, great attention is paid to the study of milling, drilling, turning, etc., from various points of view [1-7]. For example, A V Savilov and K Ahmadi [3] investigated the vibrations that occur in cutting tools. The works of Y I Zamashchikov are devoted to the study of residual stresses in the treated material [5-7]. The article [8] describes methods that were used to study the structure of carbon steel. The same methods (determination of residual stresses by the x-ray method, the study of steel by Barkhausen noise) are successfully used to study high-speed steel.

Currently, most of tools are made of high-speed steel. High demands are placed on the material of milling cutters, which are used for machining of titanium. It is known that the production technology (smelting or extrusion, etc.) affects the structure of high-speed steel. Powder steel is preferable for tool manufacture, as they are not carbide heterogeneity.

The composition and the morphology of carbides are completely formed during the smelting. Subsequent heat treatment of the tool forms the phase composition of the steel and generates secondary phases – carbides, intermetallics, etc. The most successful heat treatment of the tool is carried out in vacuum furnaces. Vacuum furnaces are not always available in companies, because of their high cost. The impossibility of quality heat treatment restrains the wide application of powder high-speed steel.
Steels heat-treated in resistance chamber furnaces and salt baths have been investigated. We studied the sensitivity of powder steels to disturbances of the heat treatment conditions. The aim of the authors was to find out how the heat treatment effects the phase composition of high-speed steels.

2. Materials and methods

High-speed steels S390 MICROCLEAN® and Fe-9%W-4%Mo-8%Co were investigated. Powder steel has a high content of carbon, vanadium, molybdenum, tungsten and chromium. The content of the main alloying elements of these steels is given in table 1.

| Steel grade        | Weight content of element, % |
|--------------------|-----------------------------|
|                    | C   | W     | Mo   | Cr   | V    | Co   |
| Fe-9%W-4%Mo-8%Co   | 1.05| 9.00  | 4.00 | 3.20 | 2.30 | 8.00 |
| S390               | 1.60| 10.50 | 2.00 | 4.80 | 5.00 | 8.00 |

Heat treatment was carried out for steels hardening. Mechanical properties were determined. Determination of the phase composition of high-speed steels was carried out on the Shimadzu X-ray diffractometer (XRD) with Cu-Kα radiation. Obtained diffractograms were compared with diffractograms of standard samples.

X-ray diffractometer Xstress 3000 G3/G3R was used. The principle and methodology of measurement are described in works [8-10].

3. Results and discussion

3.1. Study of heat treatment effect on mechanical properties

The tempering has been performed to relieve stresses. Annealing temperature is 600 °C.

Steels were gradually heated and kept at the temperatures of 500 °C (for 1.5 h) and 860 °C (for about 6 min). The third preheating before quenching was excluded for steel S390 (1050 °C), but the exposure of workpieces at the second stage of heating was increased. The second preheating (860 °C) and final preheating to a quenching temperature were performed in salt baths. Three sample parties were heated up to three different temperatures. Steels were cooled in the salt bath, and then in the oil. Triple tempering (560 °C) was carried out after quenching in chamber furnaces.

Testing of steel for hardness (HRC), impact viscosity (KC, J/cm²) and transverse bend (Rbm N/mm²) was carried out after the tempering. The results of the tests – the fluctuation ranges of values HRC, KC and Rbm – are shown in figures 1 and 2.

![Figure 1](image-url)  
**Figure 1.** Changes of transverse bend of high-speed steel S390 (a) and Fe-9%W-4%Mo-8%Co (b) depending on quenching temperature.
Figure 2. Changes of impact viscosity (a, b) and hardness (c, d) depending on quenching temperature.

Powder steel demonstrates sensitivity to the lack of 3rd preheating before quenching. The decrease of the mechanical properties S390 is observed at tempering temperature from 1182 °C. Properties of steel Fe-9%W-4%Mo-8%Co change ambiguously. There is a large range of values in the samples of the same party. Steel Fe-9%W-4%Mo-8%Co hardened at the temperature from 1240 °C has higher hardness, but its range of tensile strength (Rbm) increases, and its impact viscosity (KC) reduces.

3.2. Study of the microstructure

Investigations of the microstructure were performed on samples intended for destructive testing. After the surface preparation, the samples were studied at magnification from 250 to 1,000 times. The microstructure of steels is represented by tempered martensite and carbides (figure 3).

Very fine carbides are homogeneously distributed throughout the volume of the powder steel microstructure. Carbide heterogeneity is marked in the microstructure of steel Fe-9%W-4%Mo-8%Co: here the large carbides of different shapes, which form clusters and chains, are visible. The quenching temperature increase causes the grain growth of austenite and formation of large laminated martensite in steel Fe-9%W-4%Mo-8%Co.
3.3. Determination of the high-speed steels phase composition

Figures 4 and 5 show diffractogram of steels Fe-9%W-4%Mo-8%Co and S390.

Studies have shown that most of the designated chemical elements (Cr, Ni, Co) are in the solid solution based on iron (in martensite). Martensite is a basis of high-speed steels. Alloying elements saturation of martensite depends on treatment conditions.

There is a difference in the phase composition of steels Fe-9%W-4%Mo-8%Co and S390. For steel Fe-9%W-4%Mo-8%Co, we observe a decrease of vanadium carbide V$_8$C$_7$ (angles 2θ = 36-41°) and an increase of the diffuse peak (angles 2θ = 76-80°) corresponding to the group of Me$x$C$_y$ carbides. Complex tungsten (Fe$_3$W$_3$C) and molybdenum (Co$_6$Mo$_6$C$_2$) carbides are identified in both steels. In steel S390, cobalt is composed of complex carbides.

At the quenching temperature of 1240°C of steel Fe-9%W-4%Mo-8%Co at the angles of reflection approximately equal to 2θ = 77.5° diffused peak corresponding to carbides Cr$_2$C, Mn$_2$ZnC etc. appears. The composition of carbides corresponds to the general formula of Me$_x$C$_y$; an increase of the diffraction peak is observed for angles 2θ = 44-45°, which corresponds to an increase of proportion of solid solution based on iron – alloyed martensite. The diffraction peak of Cr$_2$C carbide (2θ = 56.5°) also appears.

In steel S390, the amount of carbide Me$_x$C$_y$ decreases after quenching from 1193 °C, which is associated with a transition of carbon in vanadium carbide V$_8$C$_7$ and an increasing of its proportion in steel. The amount of carbide Co$_6$Mo$_6$C$_2$ increases.
3.4. Determination of residual stresses

Finish milling cutters were investigated before their use. Heat treatment of the tool was carried out according to the conditions described above. Residual stresses were determined in different sections of cutters.

Measurement parameters of residual stresses: Cr-Kα radiation; the angle of diffraction – 156.4; the plane of reflection (211). Young's moduli – 217000 MPa (for S390) and 242000 MPa (for Fe-9%W-4%Mo-8%Co) and Poisson's ratio equal to 0.3 were set for the automated calculation of stresses in the program 'Xtronic'. Table 2 shows the residual stresses that are defined in different sections of the finished cutters.

| Steel grade       | Residual stresses, MPa          |
|-------------------|---------------------------------|
|                   | Cutting edge | Shank  | Milling cutter neck |
| S390              | -1016…-1174 | -610…-668 | -709…-790         |
| Fe-9%W-4%Mo-8%Co  | -1189…-1300 | -651…-682 | -726…-821         |

Figure 4. Diffractogram of steel Fe-9%W-4%Mo-8%Co (quenching temperature is 1220 °C).

Figure 5. Diffractogram of steel S390 (quenching temperature is 1182 °C).
As we can see from the table, the compressive residual stresses in the cutting edge reach high values. An excessively stressed state may be the cause of crack nucleation and premature fracture of the tool.

4. Conclusion
Our studies have shown that during heat treatment of high speed-steel in resistance chamber furnaces and in salt baths, are not possible to obtain stable mechanical properties. High-speed steels are very sensitive to changes of heat treatment conditions.

The resulting structure affects mechanical properties negatively. Eventually, the unfortunate combination of phases and the size of the structural elements are the cause of low endurance of the cutting tool.

Obtained results allow us to conclude about the important role of steel structure studying. Research findings give the opportunity to adjust the heat treatment conditions

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