Formation of technological properties and structure of high-speed powder steels and the influence of alloying components on the processes of diffusion and splicing during sintering and hot stamping

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Abstract. Using powder metallurgy, it is possible to produce more durable and wear-resistant tools made of high-speed steel. Such a tool works more effectively than a carbide tool when processing with impact and removing large allowances. But in certain niches, the tool made of high-speed steel, especially powder steel, which is characterized by greater wear resistance and strength compared to ordinary steel, retained its leadership.

1. Introduction
Powdered high-speed steel was developed in the late 60s of the last century in Sweden, and tools from it went on sale in the early 70s of the last century. The method of powder metallurgy allows you to introduce a larger number of alloying elements into steel, without reducing the strength and workability of grinding. As a result, high-speed powder steel makes a wear-resistant and durable tool that confidently copes with the load that occurs when removing a large allowance and intermittent cutting. In such conditions, the carbide tool is quickly painted. Ordinary high-speed steel consists of two main components: carbides of refractory metals and the surrounding steel base. Carbides of tungsten, molybdenum or vanadium provides the wear resistance of the tool. And the steel base surrounding them provides the strength of the tool, thanks to which it tolerates shock loads well. In the production of ordinary high-speed steel, it is poured in molten form into molds, in which it gradually cools and crystallizes. At this time, carbides are released from the melt and form areas of accumulation of carbides, located unevenly. In some cases, very large carbide inhomogeneities (up to 40 mm in diameter) can be formed. Subsequent pressure treatment of the metal reduces the carbide inhomogeneity, but it is impossible to completely get rid of it. As the number of carbide particles increases to improve wear resistance, they increase in size and accumulate as carbide inhomogeneities. This phenomenon is extremely detrimental to the strength of the tool, since the place of accumulation of carbides is the place of origin of cracks. Powdered high-speed steel, unlike ordinary steel, is fed in molten form through a special nozzle through a stream of liquid nitrogen. Steel hardens quickly in the form of small particles. There is not enough time for the formation of carbide inhomogeneities in these particles, and the result is a structure with a uniform arrangement of carbides. The resulting powder is
sieved and placed in a steel container in which a vacuum is created. Further, the contents of the container are sintered at high temperature and pressure — thus achieving uniformity of the material. This process is called hot isostatic pressing. After that, the steel is processed by pressure. The result is a high-speed steel with very small particles of carbides evenly distributed in the steel base. In the latter case, the steel powder is pressed, heated to the melting point. In this case, the structure of the material when using a bundle may be heterogeneous. High-speed steel produced by powder metallurgy combines the best properties of high-speed steel (strength) and hard alloy (wear resistance). The machinability of high-speed steel by grinding is determined by the percentage of vanadium carbides. Vanadium carbides have a higher hardness than aluminum oxide grains, which are used to make grinding wheels. For this reason, circles wear out quickly. Because of this, it takes a long time to grind ordinary high-speed steel with a high vanadium content. In high-speed powder steel, the carbides are smaller and more evenly distributed, so the process is more productive.

In recent years, high-speed powder steels have been increasingly used in the industry. This is due to the fact that the possibilities of reducing the carbide heterogeneity in steels obtained by traditional methods are almost completely exhausted. At the same time, powder metallurgy methods are one of the main directions of cardinal improvement of steel quality, since they increase the dispersion of the carbide phase and ensure its uniform distribution in the metal volume [1].

2. Materials and methods
The influence of the fractional composition on the structure and properties of high-speed powder steels was studied in [2-6]. However, the authors of these works mainly studied the properties of powders of individual fractions (-630+315; -250+160; -160+80; -80 microns), not their totality. The purpose of this work is a comprehensive study of the technological properties (fluidity, bulk density and compressibility) of high-speed steel powders of the P6M5K5 grade of various fractional compositions. The powders were obtained by spraying the liquid melt with nitrogen and divided into fractions by sequential screening of larger particles.

Table 1. The chemical composition of the powder of steel P6M5K5.

| Element | C | W | Mo | Co | Cr | V | N2 | Ni | Mn | O2 |
|---------|---|---|----|----|----|---|----|----|----|----|
| Content, % | 1.1 | 6.4 | 4.9 | 5.49 | 3.9 | 1.43 | 0.03 | 0.24 | 0.19 | 0.01 |

Recently, along with the widespread technology that involves the production of massive capsulated blanks from high-speed steel powders, their rolling or extrusion to produce bars and subsequent mechanical processing, methods for producing cutting tools directly from the powder are being used. This determines the increased requirements for the technological characteristics of the powder.

Chemical analysis was performed on a desktop scanning electron microscope JEOL JCM-6000. The appearance of the initial powder was studied using an MBS-1 stereoscopic microscope and a JSM-T20 scanning electron microscope, and the macro- and microstructure was studied using a MIM-8M microscope in reflected and polarized light. The micro hardness of the particles was determined on a PMT-3 device at a load of 1.0 N. the particle Size distribution of the powders was evaluated by sieve analysis according to GOST 18318 - 73, the bulk density and fluidity - according to GOST 19440 - 74 and GOST 20899 75, respectively.

Table 2. Fractional composition of a powder of steel P6M5K5.

| Particle size, microns | -830+630 | -630+400 | -400+200 | -200+100 | -100 |
|------------------------|----------|----------|-----------|-----------|-----|
| The share of fractions, % (wt.) | 3.7 | 7.2 | 41.8 | 23.0 | 24.3 |
In the initial powder, a fairly wide range of particle size distribution is observed. At the same time, the content of the fraction - 630 microns, which is optimal for obtaining powder compressions from high-speed steel [8], is about 96%.

![Figure 1](image)

**Figure 1.** shape (a) and microstructure (b) of the particles of the sprayed powder of steel P6M5K5. Magnification a – 100, b – 500.

Particles of high-speed steel powder, as well as other powders obtained by gas spraying, have a regular spherical shape (Figure 1, a), which mainly determines their technological properties. The particles have a fine-grained homogeneous structure with fine-dispersed carbide eutectic along the grain boundaries (Figure 1, b).

The initial powder has a very high micro hardness - at the level of 7200-10350 MPa, and it increases with a decrease in the average particle size (Figure 2, a). This is due to both the grinding of austenite grains and changes in the composition of dispersed carbides released during crystallization, as well as, possibly, additional supersaturation of austenite with carbon [4-7].

To reduce the hardness of the powder was annealed in vacuum for such a regime: heating to 850 °C, exposure 2 h, lowering the temperature to 740 °C at a speed of 30 deg/h, endurance 6 h, lowering the temperature to 550 °C at a rate of 50 deg/h, then cooling with the furnace. After annealing, the micro hardness of the particles was at the level of 3030-4080 MPa. The fractionation composition of the annealed powder corresponded to the original one.

Bulk density of both the original and annealed powder increases with increasing maximum particle size up to about 630 µm and decreases slightly from powders of fraction - 830 µm (Figure 2). Increase bulk density of powder of a polydisperse composition compared with monofractional or powders characterized by a narrower range of particle sizes, due to the fact that in the charge with a significant difference in the particle size of the voids formed between the larger particles are filled with smaller ones. The decrease in the bulk density of the powder fraction - 830 microns is probably due to the excess of a large fraction to achieve the maximum theoretically possible bulk density. After annealing, the bulk density of the powder is slightly reduced.
Figure 2. The dependence of the micro hardness of the powder high-speed steel from its fractional composition. Color black: powder in delivery condition. Color grey: powder after annealing.

Figure 3. The dependence of the bulk density of powder high-speed steel from its fractional composition. Color black: powder in delivery condition. Color grey: powder after annealing.

Figure 4. The dependence of the yield strength of the powder high-speed steel from its fractional composition. Color black: powder in delivery condition. Color grey: powder after annealing.

The fluidity of powders of smaller fractions (-100 and -200 microns) is higher compared to powders with a maximum particle size of 400 microns or more (Figure 2, c), both after annealing and in the delivery state. The deterioration of the fluidity of larger powders is explained by the fact that the average particle size of the fraction -400 microns is only an order of magnitude smaller than the size of the outlet of the funnel for measuring fluidity (2.5 mm) [8-12]. When the powder flows out, conglomerates of such particles "jam" in the area of the funnel outlet, which reduces the fluidity. Softening annealing of the powder dramatically increases its fluidity. This is due to the fact that industrial batches of dusty powder in the delivery state have a certain degree of magnetization.
Magnetization prevents segregation of the powder during transportation and processing. During annealing, structural changes occur in the material that eliminate magnetization, which increases fluidity. This is confirmed by the fact that the fluidity of the original non-annealed powder after demagnetization in the AC field is almost at the level of the annealed one [13-15].

The influence of the fractional composition of the annealed powder on its compaction during cold pressing was also studied. The blanks were formed according to the scheme of double-sided pressing on the P-150 test machine in a closed cylindrical mold with a diameter of 30 mm under a pressure of 900 MPa. The average ratio of the workpiece height to its diameter was h/d=1.

To increase the formability, a 2% plasticizer binder (a solution of rubber in gasoline) was introduced into the charge.

![Graph](image.png)

**Figure 5.** The dependence of the compactibility of powder high-speed steel from its fractional composition. Color black: the density of the samples after pressing. Color grey: the density of samples after sintering.

### 3. Results

Powders of fractions -200 and -400 microns have the best compaction (Figure 5). Satisfactory compaction is also characteristic of powders with a maximum particle size of 630 and 830 microns. Along with the relatively high fluidity and bulk density, as well as the increased yield of the product from the source powder in the state of delivery compared to smaller fractions, this indicates the preference of fractions -630 and -830 microns for the manufacture of metal-cutting tool blanks.

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