The new surface hardening method (Novik 1971) was employed for 19 experiments in each of five systems: Cr-Ti-V, Cr-Ti-Mn, Cr-Ti-Mo, Cr-V-Mo, Cr-V-Nb, Ti-V-Mo for the studied grades of hard alloys. The obtained mathematical expressions were used to plot the “composition-properties” diagrams.

3 RESEARCH RESULTS

The HTTCT of hard alloy inserts in the synthesized powder media results in the formation of continuous multicomponent carbide coatings of uniform thickness, 4-9 μm, based on complex carbides, e.g., (TiVC, (Ti,Mo)2C). The formation of multicomponent multiphase carbide coatings has complex nature and comes out from diffusion interaction of in-diffusing carbide-forming metal species with carbon contained in the tungsten and titanium carbides inside the hard alloy. The diffusion saturation of the surface of a hard alloy with carbide-forming metals from the deposition of carbide coatings onto steel stamps and hard-alloy cutting tools. The development of new wear resistant coating with microhardness of above 28,000 MPa, which exceeds the microhardness of silicon carbide, will improve the performance of hard alloy tools and permit processing materials with the hardness above HRC 60, and replacing, in certain operations, more expensive diamond tools.
powder medium is accompanied by redistribution of the elements (W, Ti and Co) in the underlying material because of the cross-term effects. Because of these reasons, the HTTCT brings about the formation of non-equilibrium phase composition of the obtained carbide coatings.

The comparative data on the maximal wear resistance and maximal microhardness of one-, two- and three-component carbide coatings in systems Cr-Ti-V, Cr-Ti-Mo, Cr-V-Mo, Cr-V-Nb and Ti-V-Mo on hard alloy BK8 are presented in Fig. 1 and Fig. 2. Similar results for hard alloy T15K6 is shown in Fig. 3 and Fig. 4. It should be outlined that the maximal level of wear resistance and microhardness of these two-component carbide coatings was chosen among three variants of coatings, and for three-component carbide coatings the choice was made among seven variants of coatings. A linear correlation has been found between the wear resistance and the microhardness of carbide coatings on the T15K6 and BK8 hard alloys in five systems: the coefficient of pair correlation is 0.74-0.99 (Tab. 1).

**Table 1.** Pair correlation coefficients between wear resistance \( K_w \) and microhardness \( H_m \) of carbide coatings on hard alloys T15K6 and BK8

| System   | Microhardness \( H_m \) | Wear resistance \( K_w \) |
|----------|--------------------------|--------------------------|
| Cr-Ti-V  | 1                        | 0.74 T15K6 0.76 BK8      |
|          | 1                        | 1                        |
| Cr-V-Nb  | 1                        | 0.88 T15K6 0.94 BK8      |
|          | 1                        | 1                        |
| Cr-Ti-Mo | 1                        | 0.94 T15K6 0.94 BK8      |
|          | 1                        | 1                        |
| Cr-V-Mo  | 1                        | 0.98 T15K6 0.99 BK8      |
|          | 1                        | 1                        |
| Ti-V-Mo  | 1                        | 0.97 T15K6 0.98 BK8      |
|          | 1                        | 1                        |

The relative wear resistance criterion, thickness of the coatings and microhardness are presented in Tab. 2.
Table 2. Relative wear resistance criterion $K_w$, thickness $\delta$, and microhardness $H_N$ of carbide coatings on T15K6 and BK8 hard alloys.

| Type of coating | $K_w$ | $H_N$, 10^4 MPa | $\delta$, µm |
|-----------------|-------|-----------------|--------------|
| One-component   |       |                 |              |
| T15K6           | 1-2.8 | 11.0-17.0       | 4-8          |
| BK8             | 1-2.4 | 10.0-17.0       | 6-9          |
| Two-component   |       |                 |              |
| T15K6           | 2.4   | 17.4-23.0       | 4-8          |
| BK8             | 3.1   | 16.1-22.0       | 6-9          |
| Three-component |       |                 |              |
| T15K6           | 4.4   | 31.0-33.0       | 4-7          |
| BK8             | 6.6   | 27.0-32.0       | 7-8          |

From Fig. 1, Fig. 2, Fig. 3, Fig. 4 and Tab. 2 it is obvious that the tested properties (microhardness and wear resistance) of three-component carbide coatings exceed those of one- and two-component coatings. This is due to the following factors: (i) the predominance of carbides having high hardness such as TiC, VC and NbC in the coating, (ii) the formation of alloy carbides containing up to 3-20% of alloying elements, and (iii) the texture of carbide grains (up to 30% of the theoretical value). The improvement of wear resistance strongly depends on the thickness of the coating, the optimal thickness being 4-7 µm. The deposition of a thicker coating onto a high alloy surface is accompanied by the formation of an interlayer of a brittle intermetallic $\gamma$-phase. It has been revealed that for cutting tools, three-component carbide coatings in the Cr-Ti-Mo and Ti-V-Mo systems with homogeneous structure, which contain up to 81% complex carbides $[\text{Ti}_x\text{Mo}_y\text{Cr}_z]$ and $[\text{Ti}_x\text{V}_y\text{Mo}_z\text{C}]$, possess maximal hardness and wear resistance at turning on a lathe.

For five three-component systems, viz. Cr-Ti-V, Cr-Ti-Mo, Cr-V-Mo, Cr-V-Nb and Ti-V-Mo, optimization of the starting powder mixtures was performed with respect to the wear resistance and microhardness of the carbide coatings produced on T15K6 and BK8 hard alloys. In this work, we present, as an example, optimization for only one system out of five of three-component systems, viz. Cr-Ti-Mo. It was performed in the following way. In accordance to the simplex method of the design experiment, the design matrix (Tab. 3) for the Cr-Ti-Mo system was composed using the obtained results of the properties of carbide coatings, where wear resistance and microhardness was used as the optimization parameter ($y$) and the mass fraction of metal oxides Cr$_2$O$_3$ ($x_1$), TiO$_2$ ($x_2$), MoO$_3$ ($x_3$) in the powder mixture were used as independent variable data.

Table 3. Design matrix and properties (relative wear resistance criterion $K_w$, and microhardness $H_N$) of carbide coatings on hard alloys T15K6 and BK8 for the Cr-Ti-Mo system.

| Cr$_2$O$_3$ ($x_1$) | TiO$_2$ ($x_2$) | MoO$_3$ ($x_3$) | Parameter $y$ | Microhardness $H_N$, 10^4 MPa | Relative wear resistance criterion $K_w$ |
|---------------------|-----------------|-----------------|---------------|------------------------------|----------------------------------------|
| 1/8                 | 1/2             | 3/4             | $y_{1112}$    | 18100                        | 16500                                  |
| 1/8                 | 1/2             | 3/4             | $y_{1112}$    | 19000                        | 17100                                  |
| 1/4                 | 1/2             | 3/4             | $y_{1112}$    | 14000                        | 14000                                  |
| 1/4                 | 1/2             | 3/4             | $y_{1112}$    | 13000                        | 14000                                  |
| 1/4                 | 1/2             | 3/4             | $y_{1112}$    | 11000                        | 10000                                  |
| 1/4                 | 1/2             | 3/4             | $y_{1112}$    | 15000                        | 13700                                  |
| 1/4                 | 1/2             | 3/4             | $y_{1112}$    | 19200                        | 18000                                  |
| 1/4                 | 1/2             | 3/4             | $y_{1112}$    | 28000                        | 24000                                  |
| 1/4                 | 1/2             | 3/4             | $y_{1112}$    | 32500                        | 31700                                  |
| 1/4                 | 1/2             | 3/4             | $y_{1112}$    | 33000                        | 31900                                  |
| 1/4                 | 1/2             | 3/4             | $y_{1112}$    | 33000                        | 31000                                  |
| 1/3                 | 1/2             | 3/4             | $y_{1112}$    | 17000                        | 16000                                  |
| 1/3                 | 1/2             | 3/4             | $y_{1112}$    | 19000                        | 19000                                  |
| 1/3                 | 1/2             | 3/4             | $y_{1112}$    | 14000                        | 13000                                  |

At that, the total amount of metal oxides Me$_2$O$_3$ in the Cr-Ti-Mo powder mixture containing 98% (50% Al$_2$O$_3$ + 35% Me$_2$O$_3$ + 15% Al) + 2% NH$_4$Cl is constant, i.e. the total amount Cr$_2$O$_3$ + TiO$_2$ + MoO$_3$ equals 100% (or 1 weight fractions).

The second, third and fourth order mathematical models describing the effect of the powder mixture composition on properties of the Cr-Ti-Mo carbide coatings, were used whereas the second and third order mathematical models appeared inadequate.

The fourth order mathematical models are the following:

**For wear resistance of carbide coatings on T15K6 hard alloys:**

\[
y = 2.0x_1+2.4x_2+x_3+2.0x_2x_3+4.4x_2x_3-0.4x_3x_1+204.8x_1x_2(x_1-x_3)+226.3x_1x_3(x_2-x_3)+244.3x_3(x_2-x_3)+1.6x_3(x_2-x_3)^2-0.5x_3(x_2-x_3)^2+3.2x_3(x_2-x_3)^2-8.0x_3^2x_1x_2+2.7x_3^2x_1x_3+5.9x_3x_2x_3^2;
\]

**For wear resistance of carbide coatings on BK8 hard alloys:**

\[
y = 2.0x_1+2.4x_2+x_3+2.0x_2x_3+1.2x_2x_3-1.6x_2x_3(x_1-x_3)+19.7x_1x_3(x_1-x_3)+123.2x_3x_1(x_2-x_3)+3.7x_3x_1x_2(x_2-x_3)+3.2x_3x_1x_2(x_2-x_3)^2+10.1x_3^2x_1x_2+9.1x_3^2x_1x_3+0.5x_3x_1x_3^2;
\]

For microhardness of carbide coatings on T15K6 hard alloys:

\[
y = 1500x_1+1700x_2+900x_1x_2+1800x_1x_3+1800x_1x_3^2+3400x_1x_3^3-4200x_2x_1x_3+5000x_2x_1x_3^2+76.7x_2x_1x_3x_1x_3+270x_2x_1x_2x_3+1200x_3x_1x_3x_3^2+5.9x_3x_2x_1x_3x_3^2-2900x_2x_1x_3+1700x_1x_3^2x_3+6770x_1x_3x_3^2;
\]

For microhardness of carbide coatings on BK8 hard alloys:

\[
y = 1400x_1+1700x_2+1000x_1x_2+1900x_1x_3+3300x_1x_3^2-4100x_2x_1x_3+4800x_2x_1x_3^2+790x_2x_1x_3x_1x_3+500x_2x_1x_2x_3+12600x_3x_1x_3x_3+800x_3x_1x_3x_3^2-5100x_1^2x_2+1700x_1x_3^2x_3+6760x_1x_3x_3^2;
\]

Numerical calculations have shown that all the above listed models are adequate.

The obtained mathematical expressions were used to plot the "composition-properties" diagrams (Fig. 5, Fig. 6, Fig. 7, Fig. 8). The diagrams show that for the Cr-Ti-Mo system, the optimal regions for all the tested properties lie approximately within the following range: 10-40% Cr$_2$O$_3$, 30-65% TiO$_2$, 15-50% MoO$_3$. Here, the wear resistance of carbide coatings on hard alloys with standard chemical composition increases by the factor of 5.9-6.4 for T15K6 and 4.2-4.7 for BK8, microhardness improves by a factor of 30,500-35,000 MPa for T15K6 and 28,500-33,000 MPa for BK8 as compared with uncoated materials.
Optimal compositions of powder mixtures for the remaining four systems were obtained in a similar way. The optimal composition regions for two grades of hard alloys appear to be the following:

- **Cr-Ti-V**: 10-45% Cr₂O₃, 40-60% TiO₂, 10-40% V₂O₅,
- **Cr-Ti-Mo**: 20-30% Cr₂O₃, 40-60% TiO₂, 20-30% MoO₃,
- **Ti-V-Mo**: 20-30% V₂O₅, 40-60% TiO₂, 20-30% MoO₃,
- **Cr-V-Nb**: 10-40% Cr₂O₃, 25-55% V₂O₅, 20-45% Nb₂O₅,
- **Cr-V-Mo**: 10-45% Cr₂O₃, 20-60% V₂O₅, 15-50% MoO₃.

The results of laboratory and industrial testing have demonstrated that these optimal compositions of the powder media permit increasing the service life of disposable (not subjected to resharpening) hard alloy tool inserts at finish and rough turning or milling by the factor of 2-6 as compared with the uncoated inserts. Hard alloy end mills of a different diameter (4-8 mm) with a Ti-V-Mo carbide coating were tested in industrial conditions by milling a hardened stamp steel 6Х6Ш3МФС (0.6% C, 6% Cr, 0.9%, 3% W, 0.8% V) with hardness HRC 62. Their wear resistance was found to increase by the factor of 6-20 in comparison with uncoated tools.

It should be noted that the use of metal oxides in the starting powder mixture instead of pure metals yielded a substantial decrease in the cost of the mixtures, by the factor of 2-10 thus improving the cost efficiency and versatility of the developed HTTCT process.

The proposed surface hardening method has the following advantages over the known technologies of coatings deposition:
- the process is simple and cost-efficient due to the use of standard equipment, cheap metal oxide media and relatively low temperature;
- thorough cleaning of the surface is not required.

### 4 CONCLUSIONS

The developed multicomponent carbide coatings permit increasing significantly the wear resistance of hard alloy cutting tools in comparison with one- and two-component coatings. Simple, cost efficient and high-performance method for depositing wear resistant carbide coatings is developed which may replace the existing technologies of surface strengthening of hard alloys cutting tools.

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