Effect of hydro-jet treatment on the adhesion of the PVD coating to the carbide substrate as a method for pretreatment of the surface

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Abstract. Traditionally, the first stages of preparing a hard alloy for coating are various mechanical, electrical, chemical, and magnetic methods to change the surface quality, which usually increases the service life and wear resistance of the tool. Among other things, hydro-jet treatment, so exposure to a high-pressure water jet at a pressure of about 250 MPa, can be used when preparing the surface for coating. Grinded surfaces after hydro-treating show better adhesion of the coating by removing an excess of the cobalt bond smeared on the surface because it is highly flexible and poorly removed by the diamond grinding wheel. Besides, the surface roughness reduced. Wear tests using the spherical recess method showed a two-three fold improvement in the wear resistance of TiN-coated samples subjected to preliminary hydro-treatment. Besides, hydro-treating avoids surface contamination and eliminates any thermal effects.

1. Introduction
In order to extend the service of carbide cutting tools and reduce the time and cost of change and adjustment, it became a tradition to apply different kinds of coatings to increase surface hardness, resistance to high-temperature corrosion failure of the temperature variation and stress, reduce adhesion with the treated material [1]. However, there is still a question of improving the quality of adhesive -cohesive bonds between the coating and the surface of the cutting base of the tool, which usually has organic and inorganic contamination on its surfaces, as well as irregularities and defects in the surface microstructure that appear as a result of mechanical and thermal loads that occur during sintering or grinding [2].

Different effects on the surface of the substrate are widely used, both before and after the coating process, to improve the adhesion of the coating to the base. Adhesion is estimated by the adhesion pressure, that is, the amount of force applied to a unit of the surface sufficient for exfoliation. An increase in this characteristic leads to an increase in the strength and crack resistance of the coating directly. It indicates the prospect of improving the performance of the tool [3]. The choice of preprocessing methods depends mainly on the functional purpose of the tool and the limitations associated with its cost [4, 5]. Traditionally, the first stages of preparing a hard alloy for coating are various mechanical, electrical, chemical, and magnetic methods for changing the surface quality, which inevitably has a significant impact on the quality of the coated tool, increasing the service life and wear resistance [6-8].
Types of preliminary preparation of the tool characterizes by the type of energy used, equipment, transport medium, and the mechanism of material removal [9]. The most widely used methods in the industry are polishing with brushes and diamond pastes, micro-abrasive jet, and magnetic vibro-abrasive treatments. To a lesser extent, laser beam, ion-beam, electrochemical, and ultrasonic processing are used [10-12].

If the water use as the medium transporting the abrasive particles, the process is called wet micro-abrasive or hydro-abrasive treatment. The only difference is that the abrasive particle mixes with water in a particular proportion, and the compressed air spray the water-abrasive suspension. As a result of experiments on surface treatment with different mechanical methods of surface preparation, it was found that the level of residual stresses during such treatment, as a rule, exceeds its values after polishing and grinding. It is also important to note that, other things being equal, the penetration depth of residual stresses increases when the size of abrasive particles increases [13].

If the water pressure significantly increased, it is quite possible to do without abrasive particles. Here, the main adjustable parameters will be the distance of the nozzle to the surface to be processed, the liquid pressure, the jet speed, and the nozzle diameter. This treatment used for surface preparation, cleaning, coating removal, water jet hardening, and other surface modification processes [14-17]. Water-jet hardening is one of the relatively new ways to use a water jet under pressure when high-speed water drops that cause local plastic deformation, which causes significant residual compressive stresses, leading to an increase in surface hardness and improving fatigue life [18]. The water-jet treatment gives a lower roughness even when the surface repeatedly treated with a stream. Also, the advantages of this method include the absence of surface contamination after treatment and the absence of thermal effects.

Concerning hard alloys, the hydro-treatment method uses to reduce large values of roughness, so-called peaks, and to remove excess content of the cobalt phase on the surface [19]. It is more plastic than carbide grains and is poorly removed by the diamond wheel during grinding, which negatively affects the adhesion of the coating to the base (Figure 1). In (Figure 1a), you can observe the traces of grinding. The binder, which contains some of the crushed tungsten carbide grains, is smeared on the surface. Water-jet processing strips the grains of tungsten carbide (Figure 1b), freeing the surface from excess cobalt. Expected that during the deposition process of the coating on the treated material, the rate of formation of bonds and connections between the coating and the substrate will increase, and the adhesion of the substrate surface to the PVD coating will improve [20,21]. This article is devoted to the consideration of this phenomenon.

![Figure 1](image_url)

*Figure 1.* a) The appearance of the surface of the carbide plate after grinding with a diamond wheel; b) The same after processing with a high-pressure water jet.

The use of hydro-abrasive treatment with the addition of quartz sand to the water leads to a significantly stronger abrasive effect on the tool. At the same time, the surface roughness deteriorates,
and intensive mechanical alloying with aluminum oxide particles occurs, so such samples excluded from the research.

2. Experimental

As samples for the study, inserts with a size of 20x40 mm made of H10 hard alloy, the chemical composition of which shown in Table 1, was used. The grain size estimation performed by comparison with reference images showed that the α-phase (WC) is medium-grained, and the γ-phase (TiC) is fine-grained. The porosity measured on the non-etched plume using the image analyzer Thixomet (Russia) was 0.35%.

Table 1. Composition of H10 hard alloy

|   | WC  | TiC | Co  | Al  | Fe  |
|---|-----|-----|-----|-----|-----|
|   | 76.2% | 15.9% | 5.89% | 1.35% | 0.13% |

The carbide inserts were processed on the Laprora beta U95 machine (Italy) with the Molemab d64 diamond wheel to simulate the surface obtained in the manufacture of tools on grinding machines according to the mode: cutting speed \(v = 18\) m/s, cutting depth \(t = 0.5\) mm, feed \(s = 1.5\) mm/min.

The hydro-treatment process was carried out on an experimental 3-coordinate hydro-jet unit with a working injection pressure of up to 250 MPa through an installed nozzle having a diameter of 0.3 mm (Figure 2a). The distance between the nozzle collimator and the plate was constant, equal to \(h = 1\) mm. Processing carried out a balanced trajectory with a step of \(a = 0.3\) mm (Figure 2b) at three liquid pressure values: \(P = 150, 200,\) and 250 MPa and at three head feed speeds \(s = 40, 60,\) and 120 mm/min. The time of the jet impact on the platform Ø 0.3 mm was \(t = 0.45, 0.3,\) and 0.15 seconds, respectively.

For convenience, comparing the impact of a high-pressure water jet in different modes, its work calculated using the formula

\[
A = Nt = QPt = Pt \frac{0.63\pi d^2}{4} \sqrt{\frac{2P}{\rho}},
\]

where \(N\) is the power of the water jet, \(t\) is the surface treatment time, \(Q\) is the water flow through the nozzle; \(P\) is the working pressure, \(d\) is the nozzle diameter, and \(\rho\) is the water density.

![Figure 2](image)

Figure 2. a) The hydro-treatment machine; b) Processing flow chart.

The content of the Co binder was monitored after exposure to a high-pressure water jet using an x-ray fluorescence spectrometer S8 TIGER (Netherlands). The surface roughness was measured using the Hommel Tester T8000 (Germany) with a Z-axis resolution of 80 nm.

PVD TiN coating with a thickness of 3 μm was applied to the treated plates using the APP-1 vacuum arc unit (Russia) [22]. The evaluation of the adhesion of coatings to the substrate made using
the scratch test with the linear increasing load up to 40 N, and the test was made by the NANOWEAR micro scratch tester (USA) using a diamond indenter with a radius at the top of 100 µm. The structure was studied using a scanning electron microscope Tescan VEGA 3 LMH (Czech republic). Wear resistance tests carried out using a device using the spherical recess method, the CALOWEAR tester (Switzerland). The resulting wells examined using a MicroCADlite (Germany) 3d scanner.

3. Results and Discussion
The adhesive properties of the coating-substrate system usually represented by the values of the critical load measured by the scratch test method [23]. It depends on several parameters related to the test conditions, such as the scratch rate, the load application rate, the radius of the diamond tip and the degree of its wear, and parameters related to the coating-substrate system itself. In most cases, researchers consider the impact of surface roughness and coating thickness, evaluating its quality, and identifying factors that affect the amount of adhesive pressure [24-26]. The pattern of residual stresses induced by mechanical treatment at the substrate preparation stage during the PVD process, which involves applying a highly stressed coating and heating to 500°C, changes, but also affects the adhesion of the coating to the substrate [27,28]. It is known that increased values of compressive residual stresses lead to higher wear and shorter tool life [29]. In our study, this factor will not consider, but the change in the content of the cobalt binder on the surface of the substrate will take into account.

Spectrometry data show that after grinding with a diamond wheel, the cobalt content in the near-surface layer of the hard alloy increases from about 6%, which corresponds to the composition of the grade, to 9%. The dynamics of excess binder flushing depending on the operation performed by a jet at different pressures shows in Figure 3. At pressures of 150-200 MPa, the amount of the element to be removed differs markedly only with the highest energy impact, so with the minimum feed value. At a pressure of 250 MPa, the process is more intensive, and the cobalt content after treatment approaches the brand concentration. Further increase in pressure is inexpedient, since high-pressure water jet can unnecessarily wash away the binder, and the strength of the hard alloy may suffer.

A similar relationship observes the surface roughness after treatment and the work performed by a high-pressure water jet. For all pressure values, the parameter under consideration is reduced from the values $R_Z = 3.5 \mu m$ typical for ground samples to 2.5 μm after hydro-jet treatment (Figure 4).

**Figure 3.** The content of cobalt in the near-surface layer of the polished hard alloy depends on the work performed by the water jet at different pressure values ($s = 60 \text{ mm/min}$).

**Figure 4.** The roughness of samples made of hard alloy depending on the work performed by the water jet at different pressure values.

Thus, with the help of high-pressure water jet treatment, it is possible to correct the chemical composition of the surface by washing off the excessive binder and insufficiently firmly held carbide particles and significantly reduce the surface roughness. Such change could not but affect the
properties of the surface during sclerometric tests since the strength of adhesion between the coating, and the substrate depends significantly on the morphology of the surface.

In **Figure 5**, data on scratching of two samples: (a) without hydro-jet processing and (b) after processing according to the mode \( P = 250 \text{ MPa}, s = 40 \text{ mm/min} \). The shift of peaks of vibroacoustic signals indicating the destruction of the coating towards higher loads on the sample on which the hydro-jet processing performs is apparent. The substrate becomes more solid by washing away some excess cobalt from the surface of the plate, which improves the adhesion of the coating to the substrate. Although, in both cases, it is possible to observe spallation behind the indenter of the
coating along the edges of the scratch, the character of the flaking of the coating changes slightly (Figure 6). But the area of delaminations and their width reduced.

![Figure 6. Destruction of the TiN coating on the H10 hard alloy by a diamond indenter a) without treatment, b) after hydro-jet treatment according to the mode: P = 250 MPa, s = 40 mm/min.](image)

Figure 6 shows the dependence of the force $F$, at which the first cracks in the coating occur, on the work performed by the water jet. It can see that due to hydro-jet treatment, its value increased from 18 N to 24 N.

![Figure 7. Dependence of the amount of force on the indenter that causes the first crack on the coating during sclerometric, depending on the work performed by the water jet during hydro-jet processing.](image)

![Figure 8. Curves of changes in the volume of produced material depending on the wear time for a sample of hard alloy with TiN coating (1) and the same sample with pre-coating hydro-treatment at a jet pressure of 250 MPa (2).](image)

Improving the adhesive bond between the coating and the base has a positive effect on wear resistance [30]. When testing the wear resistance of the surface layer, several holes made on each of the samples, which forms with an increase in the time step. All other parameters remained unchanged: the normal force of 2H; the speed of the shaft 735 rpm; the diameter of the ball 20 mm. The curves were constructed in the coordinates "wear time – the volume of the removed material". Presented in Figure 8, dependences show that the volume of removed material for samples treated with a high-pressure water jet at a pressure of 250 MPa before applying a wear-resistant coating reduces by up to 3 times.
4. Conclusion
The adhesion of the coating to the carbide substrate and its wear resistance significantly depends on the pre-treatment of the tool. In this way, the method of processing the surface of a carbide tool with a high-pressure water jet copes with the task of removing the formed excess binder and reducing the surface roughness after the grinding operation.

It is convenient to use the calculated amount of work performed by the water jet to assess the impact of hydro-treating on a hard alloy. However, the working injection pressure must be at least 200 MPa, so that the impact is significant and not more than 250 MPa, so as not to damage the structure of the base. Accordingly, at a lower pressure, it is necessary to increase the processing time.

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