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Communication

Initial Study of the Effect of Some PVD Coatings ("TiN/AlTiN" and "TiAlN/a-C:N") on the Wear Resistance of Wood Drilling Tools

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Abstract: The wear of drills when processing wood-based boards is an important problem in industrial practice. The main objective of the study was to experimentally check whether two types of PVD coatings (multilayer nanocomposite "TiN/AlTiN" and double-layer coatings "TiAlN/a-C:N") increase the wear resistance of the drill bits significantly (in terms of statistics). The typical two-blade drill bits intended for drilling in wood-based panels were used. During the experiments, the holes were drilled in samples made of commercial raw three-layer particleboard with the spindle speed of 4500 rpm, and the feed per revolution was 0.15 mm. The tool wear was monitored using a microscope. The advantage (greater resistance to wear) of both of the tested coatings ("TiN/AlTiN" and "TiAlN/a-C:N") over raw cemented carbide was statistically significant in the initial period of machining (before 800 holes were drilled). Unfortunately, in the final period (when the number of holes drilled was over 800), only one coating ("TiN/AlTiN") retained its advantage over raw cemented carbide. The effect of the second coating ("TiAlN/a-C:N") turned out to be statistically insignificant.

Keywords: anti-wear coatings; magnetron sputtering; tool life; tool wear

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1. Introduction

The wear of cutting tools (including drills) when processing wood-based boards is a significant problem in industrial practice. Usually, there is a close relationship between tool wear and product quality. For example, dimensional accuracy drops [1] and the problem of delamination gets worse [2]. That is why drill condition monitoring systems intended for furniture factories are so much in demand [3–5]. Sometimes the concept of integrating drill wear monitoring with product quality monitoring is even considered [6]. Either way, monitoring is obviously not all there is to do. Striving during the machining of wood-based materials should be a very important development trend (both from a scientific and a practical point of view) [7].

The issue of reducing tool wear in woodworking is not simple. The mechanism of this wear progress is still not fully understood but what is well known is that it is absolutely different than what occurs in the case of metal cutting [8–10]. There are many reasons for this divergence. First, both the internal structure and the chemical properties of the workpieces are completely different. What is more, wood-based materials can be naturally contaminated with sand. Moreover, woodworking parameters (i.e., cutting speed and feed rate) are much greater. Tool cooling conditions are also much more troublesome—wood-based materials are good heat insulators and are processed without any cooling or lubricating liquids. As a result, the temperature of the cutting edge can get as high as 900 °C [9]. All these factors mean that extending tool life is not easy and requires the use of advanced techniques. Therefore, for many years, a lot of intensive research has been carried out on anti-wear coatings that could be used for this very purpose. Modified knives for milling cutter heads were the most studied idea [8,10–13]. Other types of tools were also tested, of course (such as drills [7], planer knives [14], turning knives [15], router bits [16], or knives for wood rotary peeling process [17]). The most common tool-coating techniques are currently chemical vapor deposition (CVD) or physical vapor deposition (PVD), which can be used for thin-film deposition. The PVD or CVD coatings are generally used to improve hardness, increase wear resistance, and prevent oxidation [18–20].

One of the most interesting coatings is carbon-based (diamond-like carbon, "DLC"). Depending on the sp^2/sp^3 (hybrid carbon structures) ratio, there is a wide range of DLC coatings. The ratio of sp^3/sp^2 in the DLC coatings can be adjusted to generate coatings with more diamond or more graphite-like properties depending on the application requirements. A popular version of the DLC coating is the amorphous carbonitride layer ("a-CN"), with a hardness of about 1100 HV.

Other popular anti-wear coatings are titanium chemical compounds, such as "TiN", "TiCN", and "TiSiN" [21], or aluminum-based coatings, such as "AlCrN", TiAlN", and "AlTiN" [8,14]. Our previous research has shown that the most promising coatings for the protection of woodworking tools are: multilayer nanocomposite "TiN/AlTiN" and double-layer coatings "TiAlN/a-C:N" [8,13]. They have proven to be quite advantageous when milling a standard three-layer chipboard. This article presents an initial study of the real suitability of these coatings (deposited by PVD techniques) for increasing the durability of drill bits. The review of the specialized literature showed that the wear resistance of any woodworking drills modified in this way has never been tested before.

2. Materials and Methods

The experimental research was carried out using a standard CNC (Computerized Numerical Control) machining center (Busellato Jet 100, Casadei Busellato Team Work, Thiene, Italy), which is shown in Figure 1.

Figure 1. General view of a machining center (Busellato Jet 100), which was used in the study (1—mobile stand, machine body element, 2—spindle head, 3—elements of vacuum working table, 4—spindle dust brushes, 5—dust extraction system pipe).

Typical two-blade drill bits intended for drilling in wood-based panels were used. These were tools with a diameter of 12 mm and with blades made of tungsten cemented carbide K05. The drills (catalog symbol—K0500013, WP-01, FABA S.A., Baboszewo, Poland) were a commercial product of one of the most popular Polish manufacturers of woodworking tools, but some of them were laboratory-modified for research purposes using the advanced PVD technique. All PVD coatings were custom-made by specialists from the Jozef Stefan Institute (Ljubliana, Slovenia).

A total of 12 brand new-drills were used. They were randomly divided into three groups (so there were 4 drill bits in each group): Group A, Group B, and Group C. Tools from Group A (drill bits marked with symbols A1–A4) were left without any modification—thus, a control group was created. The drill bits from the remaining two groups were modified by the application of the two different coatings: "TiN/AlTiN" (Group B) and "TiAlN/a-C:N" (Group C). Drill bits used in Groups B and C were marked with symbols B1–B4 and C1–C4, respectively. A general view of the drill bits from all groups (Groups A, B, and C) is shown in Figure 2.

Figure 2. General view of the drill bits from all groups (from the left: Groups A, B, and C). Prior to their insertion in the deposition system, the tools were cleaned in an ultra-sonic bath and dried using hot air. The magnetron sputter deposition system CC800/9 sinOx ML (CC9, Cemecon, Würselen, Germany) was used for the deposition of both nanolayer "nl-AlTiN/TiN" and double-layer "TiAlN/a-CN" hard coatings. In this system, the chamber is equipped with four rectangular magnetron sputtering cathodes (500 × 88 mm), which operate in DC. Target configurations for the deposition of both coatings are presented in Figures 3 and 4. Three "AlTi" and one "Ti" target were used in order to prepare the "nl-AlTiN/TiN" coating. During the deposition of the "AlTiN" coating, only the "AlTi" targets were active, while during the deposition of "TiN" only one "Ti" target was active. In order to achieve a nanolayer structure, the substrates were positioned on the two-fold rotation mounting at the planetary substrate holding system. The "nl-AlTiN/TiN" coating is composed of about 200 individual layers of "AlTiN" and "TiN". Three "TiAl" and one pyrolytic graphite target were used to prepare the "TiAlN/a-CN" coating. During the deposition of the "TiAlN" coating, only the "TiAl" targets were active, while during the deposition of "a-CN", only one graphite target was active. Prior to the deposition, the chamber was evacuated to a base pressure of 3 mPa, and heated to around 450 °C. In the next step, the substrates were ion-etched for 15 min in a mid-frequency plasma (Ar and Kr gas mixture, 240 kHz, duty cycle 1600 ns), with a bias voltage of 650 V, applied to the substrate table. MF etching was followed by so-called «booster» etching, where the working gas is injected through upper and lower "booster" etch nozzles (i.e., the hollow cathode), where intensive ionization of the working gas (Ar, Kr) occurs. Such additional discharge enhances the plasma density and thus the intensity of the etching process. Coatings were deposited in a mixture of argon (160 mL/min), krypton (110 mL/min), and nitrogen (80 mL/min) at a total pressure of 0.66 Pa. The total thickness of this multilayer coating is about 4 μm.

The surface topography of the modified drill bits was observed using a scanning electron microscope (Hitachi SU-70, Tokyo, Japan). Scanning electron microscope (SEM) images of a magnetron sputtered "AlTiN" and "a-C:N" outer coatings are shown in Figure 5 and Figure 6, respectively. The magnification in both photos is the same, and the differences in the topography of the different coatings are clearly visible.

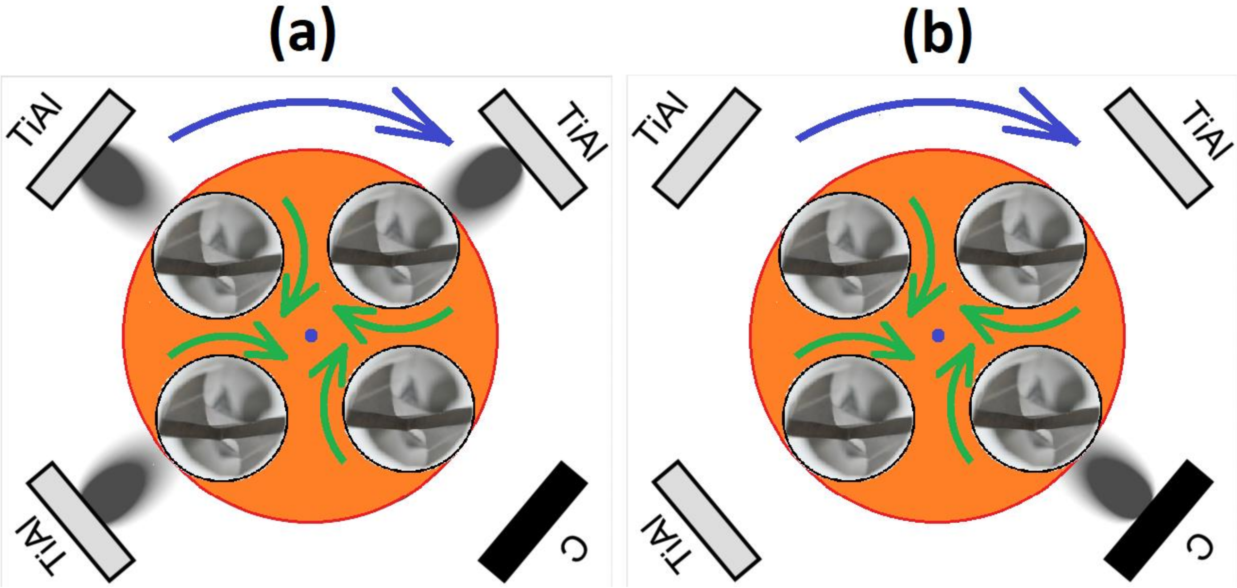


Figure 3. Configurations of the targets for deposition of "TiAlN" (**a**) and "a-CN layers" (**b**), which compose the double "TiAlN/a-CN" coating.

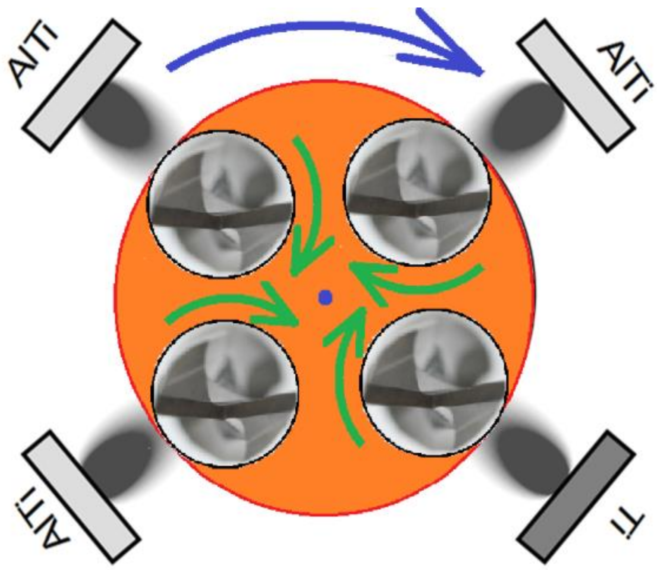


Figure 4. Configurations of the multilayer "TiN/AlTiN" coating targets.

During the experiments, the holes were drilled with the spindle speed of 4500 rpm and the feed per revolution of 0.15 mm. The condition of each drill bit was repeatedly checked after another 100 holes were made. This check was performed in the traditional way—the size of wear of the external corner of the drill (so-called the outer corner wear [22]) was measured using a microscope equipped with a digital camera (Mitutoyo—505—Mitutoyo Corporation, Kanagawa, Japan). Outer corner wear (marked in this study with the symbol W) is a standard drill wear indicator, and the method of its measuring is well-known and illustrated in the specialized literature, e.g., [22,23]. The final measurement (W) was given in millimeters (Figure 7).

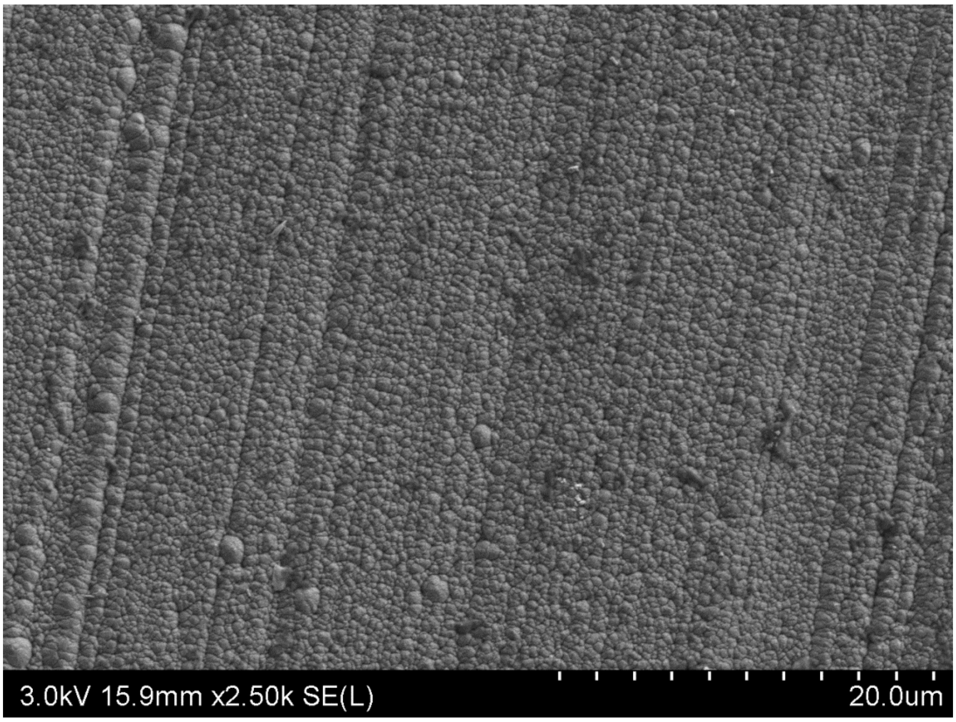


Figure 5. SEM image of the "AlTiN" coating (Hitachi SU-70 scanning electron microscope).

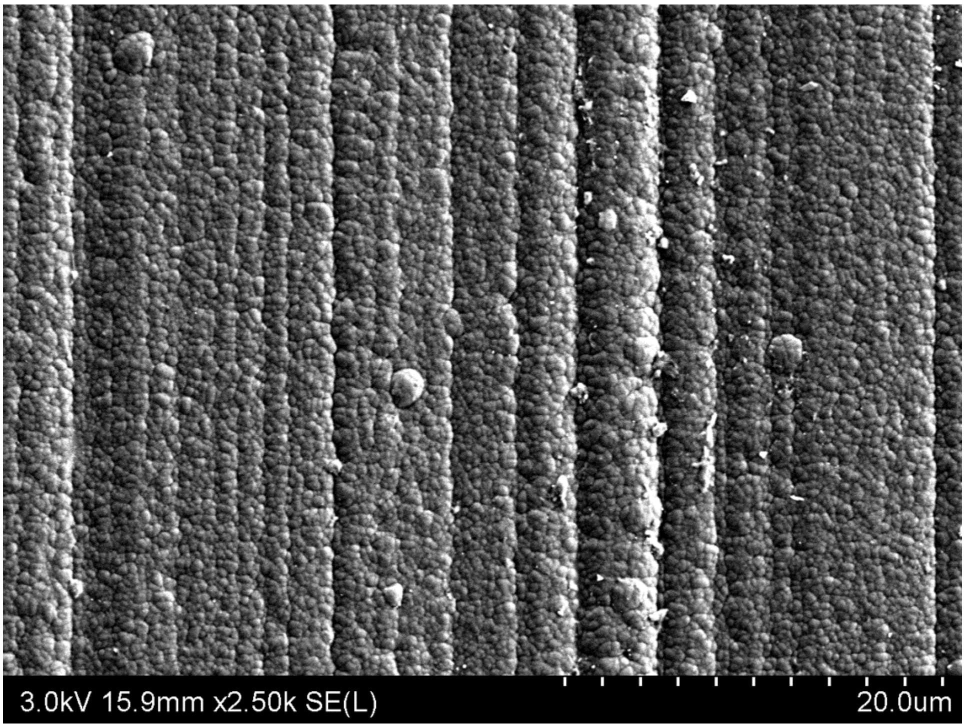


Figure 6. SEM image of the "a-C:N" coating (Hitachi SU-70 scanning electron microscope).

The tool wear indicator was determined separately for each of the drill bit blades. Therefore, the wear resistance (durability) of each of the 24 blades (a reminder: 12 two-blades drills were used) was monitored and analyzed separately.

The current value of the drill wear indicator (W) was determined using a microscope after every hundred holes had been drilled. The detailed experimental schedule presented in a standard flowchart (algorithm diagram) is shown in Figure 8. The experimental procedure performed for each of the 12 drills is presented in this figure in a metaphorical form (as if it were an algorithm of a computer program and not a procedure performed by a human being). After the experiment was completed, the standard analysis of variance (ANOVA) was used to check whether the anti-wear coatings were really effective (i.e., whether they significantly, from a statistical standpoint, have reduced tool wear in comparison to the control group).

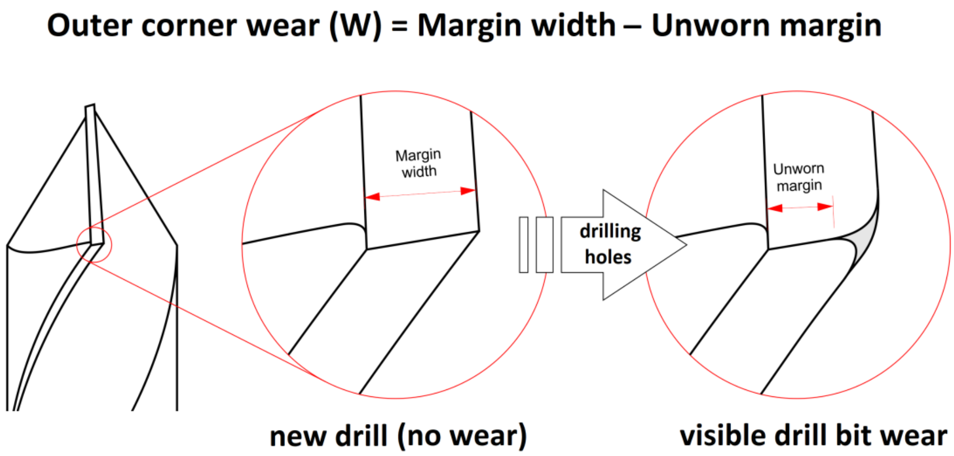


Figure 7. The outer corner wear (W) determination.

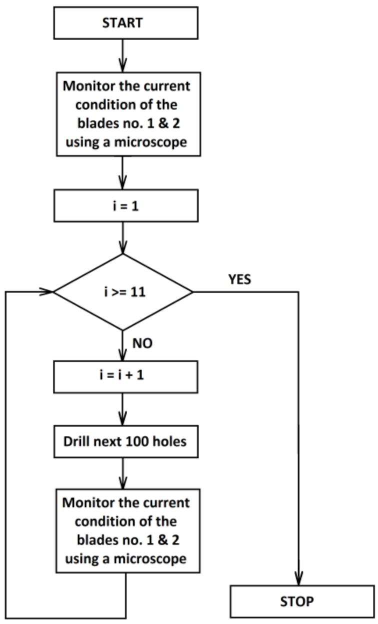


Figure 8. The experimental schedule as a standard flowchart; that is, in a metaphorical form (as if it were an algorithm of a computer program and not a procedure performed by a human being).

All of the holes (1100 holes for each tool) were drilled in samples made of standard (commercial) raw three-layer particleboard (produced by Swiss Krono Group, Lucerne, Switzerland). The basic physical and mechanical properties of the board used in the study were determined using adequate international standards and are presented in Table 1. The average density was determined in accordance with [24]. The flexural strength and the elastic modulus were determined according to [25]. The tensile strength was determined in accordance with [26]. The resistance to axial withdrawal of screws was determined in accordance with [27]. All material strength tests were carried out using Instron 3382 universal testing machine (Instron, Norwood, MA, USA. The hardness of the board was measured according to [28], using a digital Brinell CV-3000LDB tester (CV Instruments, Camberley, England). The determination of mineral contamination (sand) content was carried out according to [29]. The determination of the swelling in thickness after immersion in water was based on [30].

Table 1. Basic physical and mechanical properties of the particleboard [8].

Property Name	Physical Unit	Value
Density	(kg/m^3)	650
Flexural strength	(N/mm^2)	13.1
Elastic modulus	(N/mm^2)	3200
Tensile strength	(N/mm^2)	0.37
Strength in pull out of screws test	(N/mm)	70.9
Hardness in Brinnel scale	(HB)	2.61
Mineral contamination	(%)	0.18
Swelling 24 h	(%)	25.6

3. Results and Discussion

The results of the measurement of the outer corner wear (W) after drilling consecutive series of 100 holes are presented in two ways: tabularly (Tables 2–4) and graphically—the blade wear curves for drill bits from all the compared groups (Groups A, B, and C) are shown in Figure 9, Figure 10 and Figure 11 (respectively).

Table 2. The values of outer corner wear (W) measured while monitoring the condition of drill bits from Group A (control group containing four two-blade tools that were unmodified). The table contains the data shown in Figure 9.

No. of Hole	Progress of Drill Blades Wear—W (mm) No. of Drill/No. of Blade							
	A1/1	A1/2	A2/1	A2/2	A3/1	A3/2	A4/1	A4/2
100	0.11	0.067	0.052	0.056	0.022	0.006	0.045	0.056
200	0.12	0.082	0.059	0.06	0.024	0.016	0.054	0.064
300	0.13	0.092	0.079	0.065	0.03	0.04	0.062	0.073
400	0.155	0.138	0.08	0.07	0.051	0.049	0.07	0.081
500	0.158	0.146	0.081	0.096	0.054	0.053	0.071	0.082
600	0.162	0.148	0.082	0.105	0.056	0.062	0.072	0.083
700	0.166	0.15	0.083	0.111	0.057	0.064	0.083	0.096
800	0.168	0.152	0.102	0.118	0.061	0.067	0.092	0.118
900	0.172	0.153	0.117	0.122	0.065	0.07	0.097	0.12
1000	0.173	0.156	0.123	0.13	0.069	0.071	0.102	0.123
1100	0.176	0.165	0.127	0.133	0.07	0.072	0.107	0.126

Table 3. The values of outer corner wear (W) measured while monitoring the condition of drill bits from Group B (experimental group containing four two-blade tools that were coated with "TiN/AlTiN"). The table contains the data shown in Figure 10.

No. of Hole	Progress of Drill Blades Wear—W (mm) No. of Drill/No. of Blade							
	B1/1	**B1/2**	**B2/1**	**B2/2**	**B3/1**	**B3/2**	**B4/1**	**B4/2**
100	0.062	0.064	0.026	0.007	0.038	0.017	0.066	0.028
200	0.068	0.078	0.049	0.017	0.043	0.026	0.069	0.054
300	0.081	0.092	0.059	0.022	0.048	0.04	0.07	0.061
400	0.084	0.097	0.067	0.027	0.052	0.051	0.075	0.062
500	0.112	0.103	0.068	0.03	0.051	0.063	0.077	0.066
600	0.115	0.104	0.077	0.046	0.05	0.065	0.079	0.07
700	0.123	0.105	0.086	0.052	0.082	0.067	0.09	0.071
800	0.124	0.108	0.095	0.066	0.088	0.069	0.102	0.072
900	0.128	0.11	0.096	0.072	0.089	0.072	0.103	0.073
1000	0.129	0.113	0.097	0.078	0.09	0.075	0.104	0.074
1100	0.13	0.115	0.098	0.091	0.091	0.076	0.105	0.075

Table 4. The values of outer corner wear (W) measured while monitoring the condition of drill bits from Group C (experimental group containing four two-blade tools that were coated with "TiAlN/a-C:N"). The table contains the data shown in Figure 11.

No. of Hole	Progress of Drill Blades Wear—W (mm) No. of Drill/No. of Blade							
	C1/1	**C1/2**	**C2/1**	**C2/2**	**C3/1**	**C3/2**	**C4/1**	**C4/2**
100	0.056	0.026	0.031	0.008	0.019	0.036	0.034	0.068
200	0.074	0.038	0.035	0.018	0.028	0.039	0.048	0.073
300	0.08	0.048	0.046	0.021	0.036	0.042	0.062	0.08
400	0.088	0.054	0.049	0.025	0.043	0.074	0.068	0.088
500	0.094	0.077	0.066	0.054	0.049	0.077	0.077	0.089
600	0.114	0.094	0.071	0.058	0.058	0.085	0.082	0.102
700	0.128	0.104	0.078	0.059	0.066	0.093	0.086	0.115
800	0.15	0.114	0.086	0.06	0.074	0.103	0.091	0.117
900	0.157	0.14	0.087	0.061	0.082	0.114	0.102	0.119
1000	0.168	0.143	0.088	0.062	0.094	0.125	0.103	0.121
1100	0.171	0.146	0.089	0.063	0.105	0.127	0.104	0.124

The large variation in the rate of wear of individual blades, especially in Group A (the control group) and Group C (the experimental group containing tools that were coated with "TiAlN/a-C:N"), is worth noting. Group B (the experimental group containing tools that were coated with "TiN/AlTiN") performs much better in this regard. This variation may stem from a number of random reasons, including the variability of the properties (machinability) of the particleboard. To minimize this experimental disturbance, the correlation between the wear of two blades (blade no. 1 and blade no. 2) used in the same drill was analyzed (Figures 12–14). It is worth noting that both of these blades were cutting basically the same material. This way, it was surprising that the aforementioned correlation was the highest in Group A (coefficient of determination R^2 = 0.85) and the lowest in Group C (R^2 = 0.59). For Group B, the coefficient of determination was rather moderate (R^2 = 0.74). This suggests that the durability of standard (raw) tungsten cemented carbide K05 is a bit more uniform than the durability of the PVD coatings. Moreover, it seems like there were some issues with the uniform deposition of the "TiAlN/a-C:N" coating in particular.

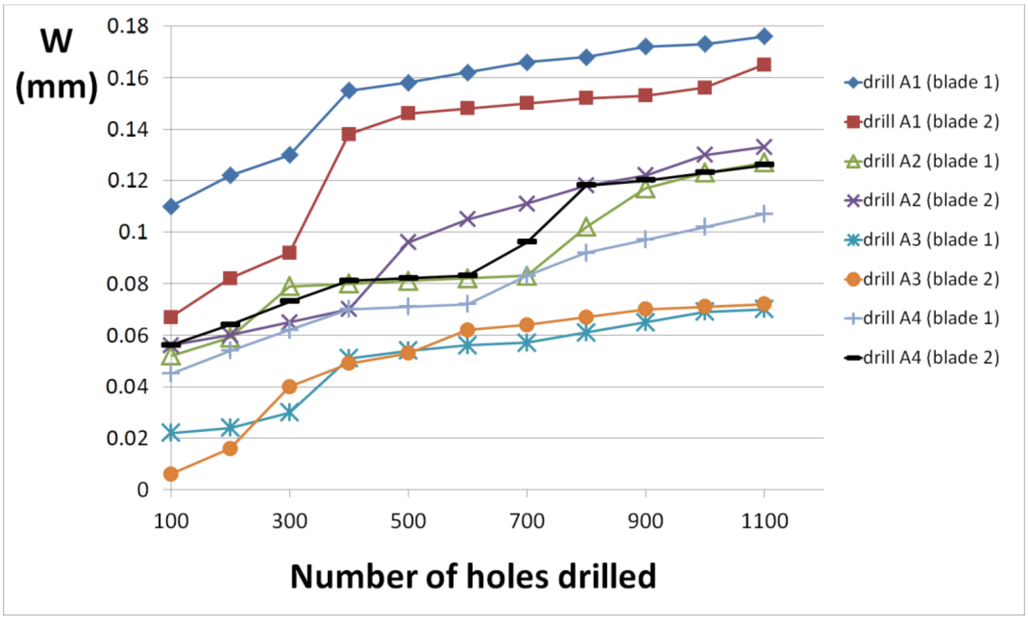


Figure 9. The blade wear curves for drill bits from Group A (control group containing four two-blade tools that were unmodified). R^2 stands for the coefficient of determination.

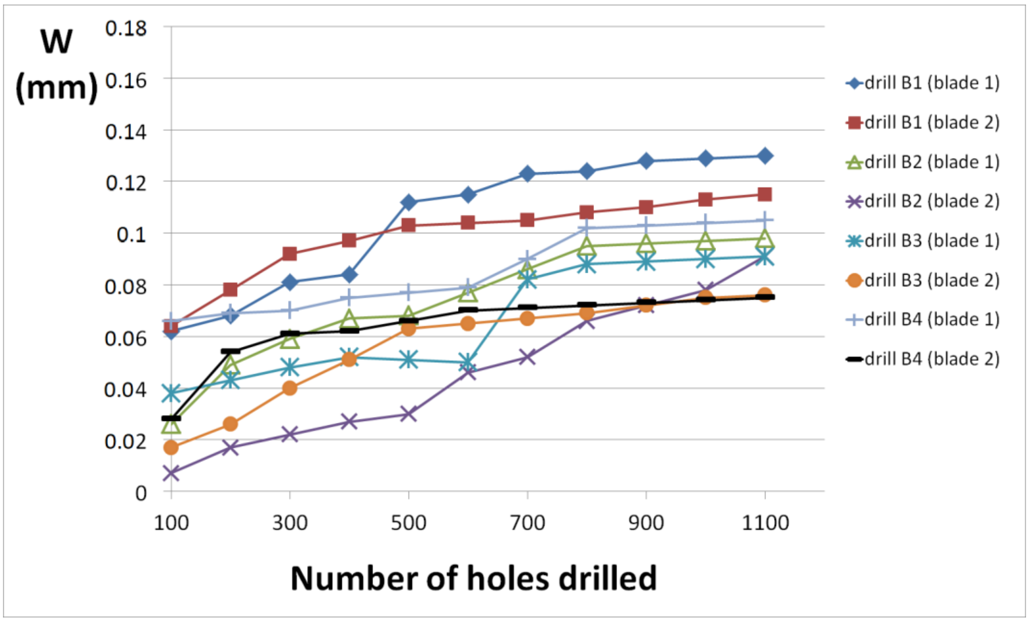


Figure 10. The blade wear curves for drill bits from Group B (experimental group containing four two-blade tools that were coated with "TiN/AlTiN"). R^2 stands for the coefficient of determination.

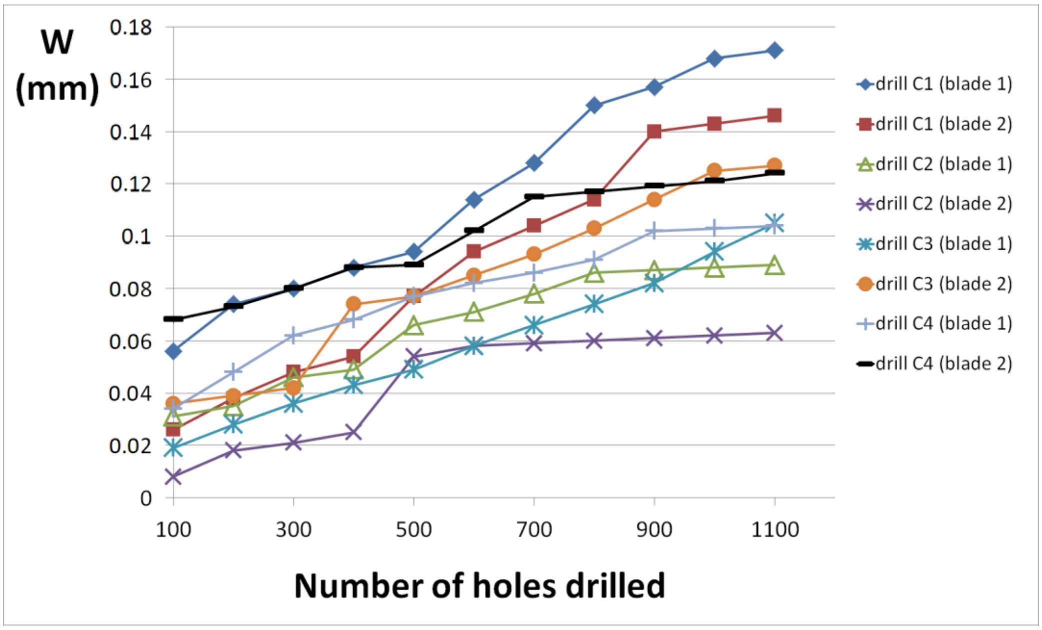


Figure 11. The blade wear curves for drill bits from Group C (experimental group containing four two-blade tools that were coated with "TiAlN/a-C:N"). R^2 stands for the coefficient of determination.

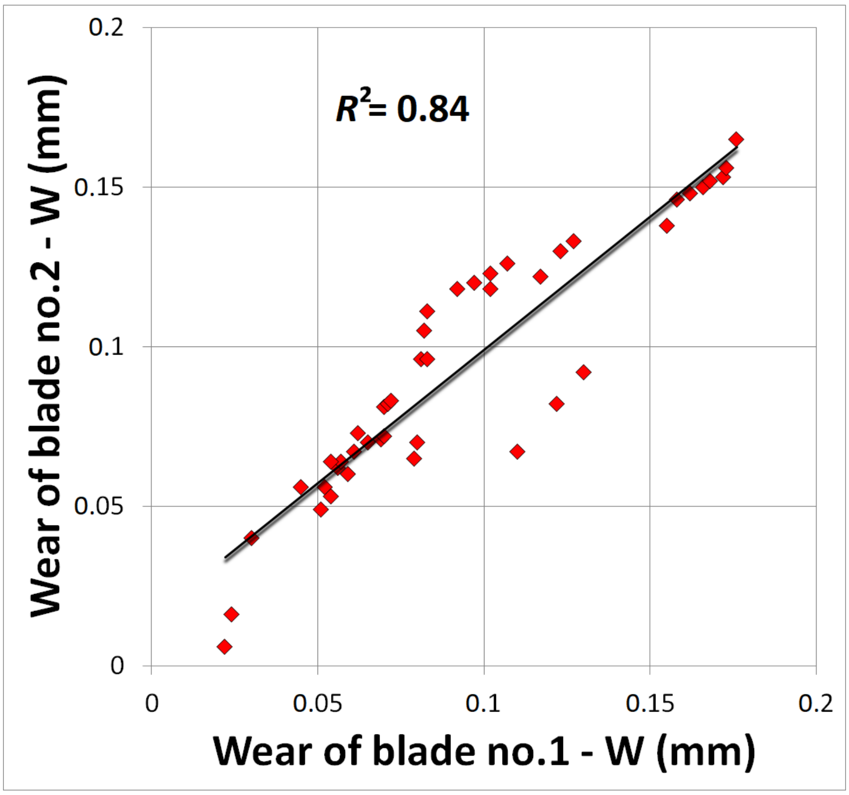


Figure 12. The correlation between the wear of two blades used in the same drill for tools belonging to Group A (control group containing four two-blade tools that were unmodified).

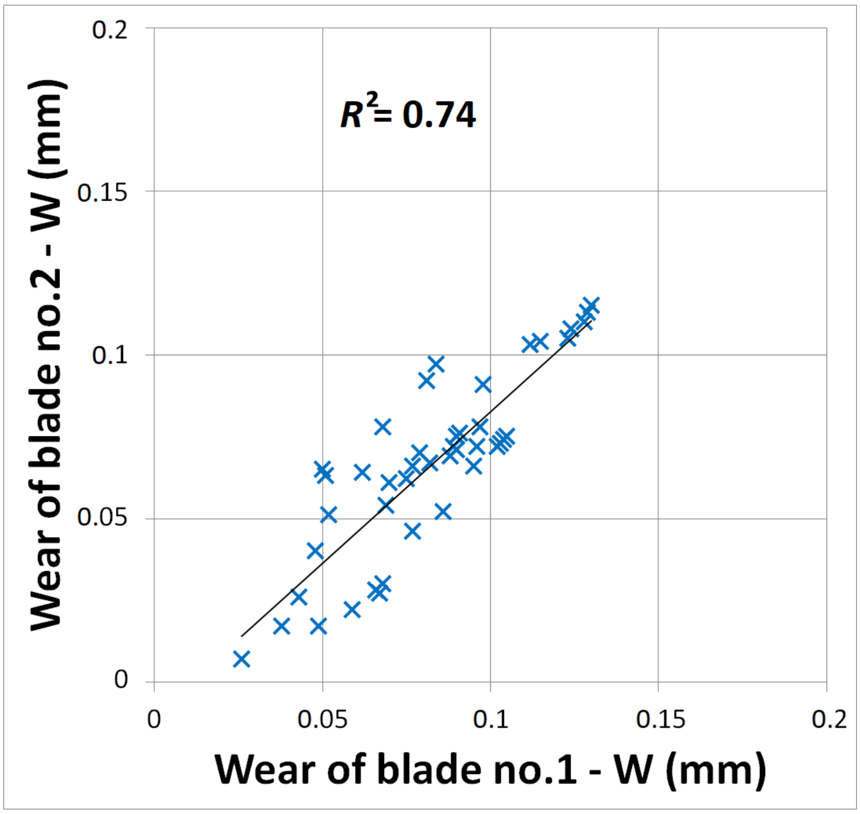


Figure 13. The correlation between the wear of two blades used in the same drill for tools belonging to Group B (experimental group containing four two-blade tools that were coated with "TiN/AlTiN").

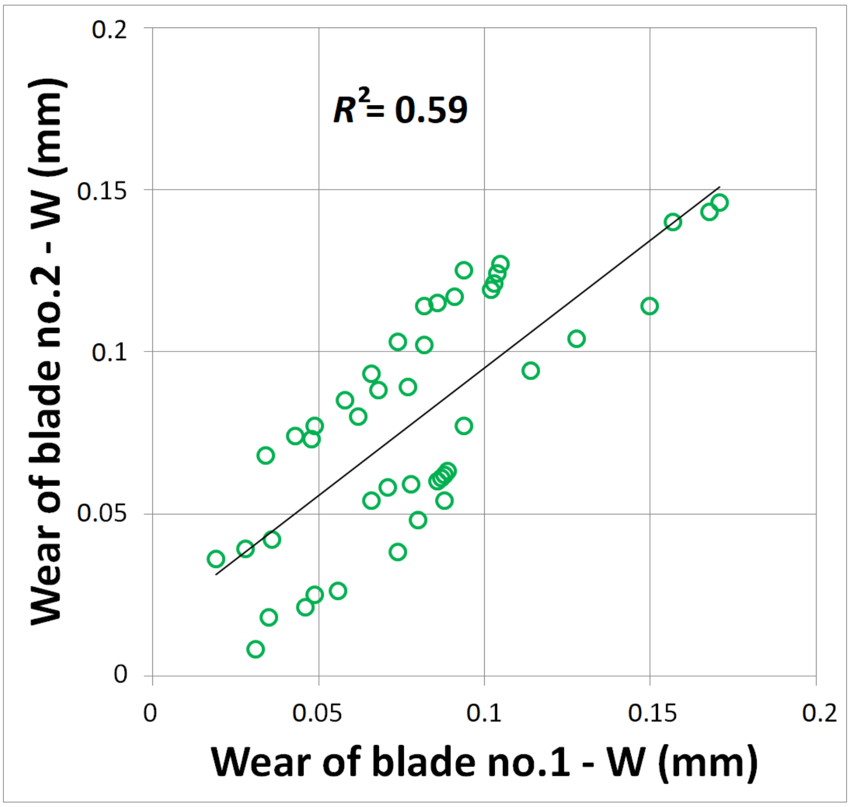


Figure 14. The correlation between the wear of two blades used in the same drill for tools belonging to Group C (experimental group containing four two-blade tools that were coated with "TiAlN/a-C:N").

However, the most important data (from the point of view of the basic purpose of this study) is what is presented in Figure 15. This figure shows the averaged wear curves for the compared groups (Groups A, B, and C). The overall shape of these curves suggests that both of the anti-wear coatings were quite effective—especially in the early stages of machining (before 700 holes were drilled), when, probably, none of the coating had completely worn off. This intuitive conclusion was supported by the results of one-way analysis of variance (ANOVA), which is commonly used to determine whether there are any statistically significant differences between two or more sample groups that need to be compared. In the study, ANOVA was used to check whether the compared groups of drills were significantly different (in terms of wear resistance). Therefore, the data presented in Tables 2–4 were analyzed to determine whether the mean value of tool wear (W), which was calculated for drills from the control group (A), differed from the analog means for drills from the experimental groups (B and C). The groups were compared in pairs (A vs. B and A vs. C). The detailed results of all ANOVA tests are presented in Figure 16. It shows the original tables automatically generated in the MATLAB (The MathWorks, Inc., Natick, MA, USA) environment. The statistical significance of the differences was determined by the probability of Type I error (the error of rejecting a null hypothesis when it is, in fact, true). This probability (p-value) is given in the last column (called "Prob > F") in the tables shown in Figure 16. The significance level is usually set at 0.05, which means that the acceptable risk of Type I error cannot exceed 5%. Therefore, the intergroup difference is only statistically significant if the p-value is lower than 0.05.

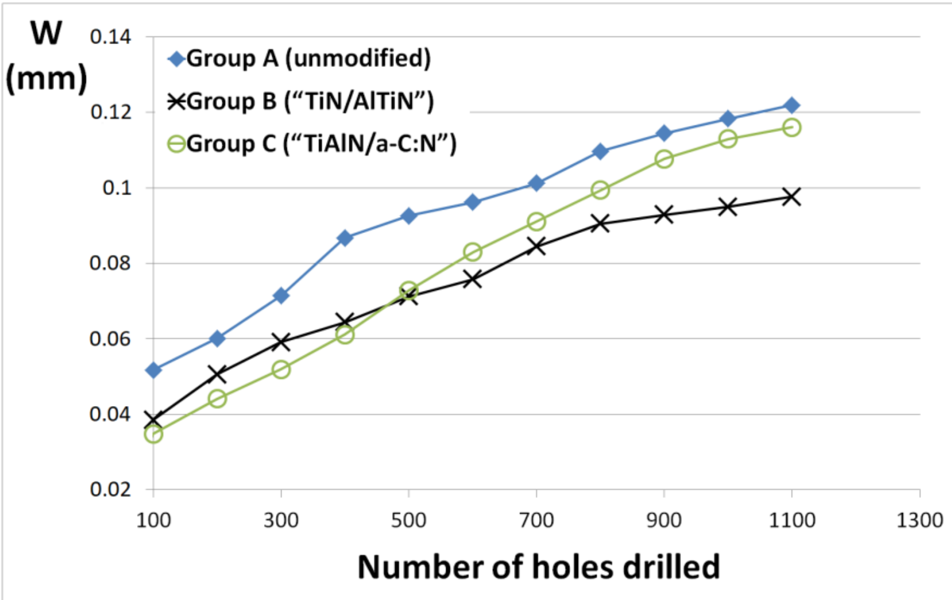
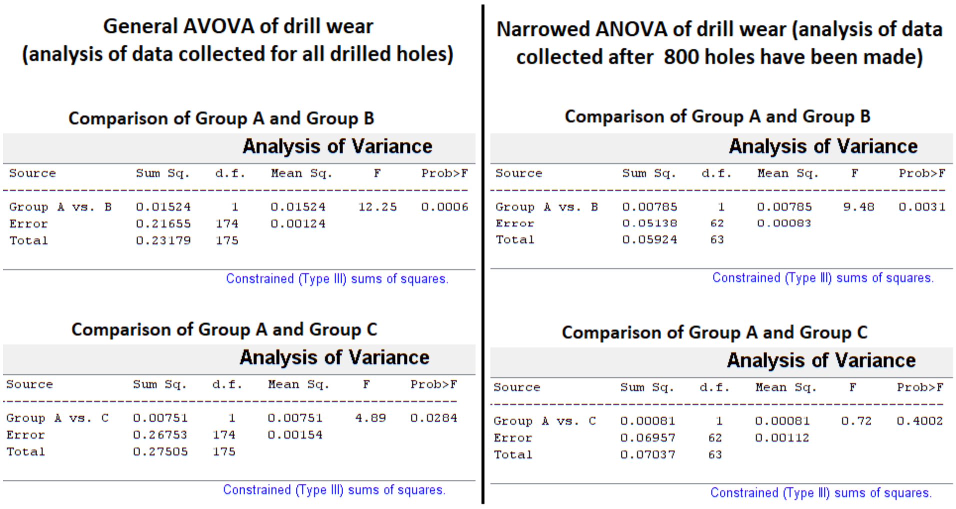


Figure 15. The averaged blade wear curves for all groups (Groups A, B, and C).

The general analysis of variance (i.e., the analysis of all the drilled holes' data contained in Tables 2–4) showed the advantage of both coatings ("TiN/AlTiN" and "TiAlN/a-C:N") over raw cemented carbide was statistically significant (p-value = 0.0006 < 0.05 and p-value = 0.0284 < 0.05, respectively). However, a more detailed and narrowed statistical analysis (which was carried out when the number of drilled holes was 800 or more; that is, the analysis of data contained only in the last 4 rows of Tables 2–4) confirmed the usefulness of only one coating—"TiN/AlTiN" (p-value = 0.0031 < 0.05). In this case, the influence of the "TiAlN/a-C:N" coating on the tool condition turned out to be statistically insignificant (p-value = 0.4 > 0.05).



General AVOVA of drill wear (analysis of data collected for all drilled holes)

Comparison of Group A and Group B

Analysis of Variance

Source	Sum Sq.	d.f.	Mean Sq.	F	Prob>F
Group A vs. B	0.01524	1	0.01524	12.25	0.0006
Error	0.21655	174	0.00124		
Total	0.23179	175			

Constrained (Type III) sums of squares.

Comparison of Group A and Group C

Analysis of Variance

Source	Sum Sq.	d.f.	Mean Sq.	F	Prob>F
Group A vs. C	0.00751	1	0.00751	4.89	0.0284
Error	0.26753	174	0.00154		
Total	0.27505	175			

Constrained (Type III) sums of squares.

Narrowed ANOVA of drill wear (analysis of data collected after 800 holes have been made)

Comparison of Group A and Group B

Analysis of Variance

Source	Sum Sq.	d.f.	Mean Sq.	F	Prob>F
Group A vs. B	0.00785	1	0.00785	9.48	0.0031
Error	0.05138	62	0.00083		
Total	0.05924	63			

Constrained (Type III) sums of squares.

Comparison of Group A and Group C

Analysis of Variance

Source	Sum Sq.	d.f.	Mean Sq.	F	Prob>F
Group A vs. C	0.00081	1	0.00081	0.72	0.4002
Error	0.06957	62	0.00112		
Total	0.07037	63			

Constrained (Type III) sums of squares.

Figure 16. The detailed results of all ANOVA tests carried out in the study.

All these conclusions are generally consistent with the experimental data to which a previous study (with the use of milling tools) has led [8]. The data from study [8] makes it possible to show the general effect of the 5 µm thick coating on the cutting distance needed for the same (VB = 0.2 mm) tool wear limit (Figure 17). For full clarity, it should be added that the symbol "VB" represents flank wear, which is the most commonly used tool wear indicator in the case of milling tools [1,2,4]. Moreover, the cutting distance was used as the alternative—to the tool life—indicator of the tool's durability. Of course, both of these indicators are closely related to each other (knowing the cutting speed, it is possible to convert the tool life into the cutting distance or vice versa). Moreover, it is necessary to explain that the chart shown in Figure 15 is not literally quoted from an earlier publication [8] but is strictly based on the tabular data contained therein.

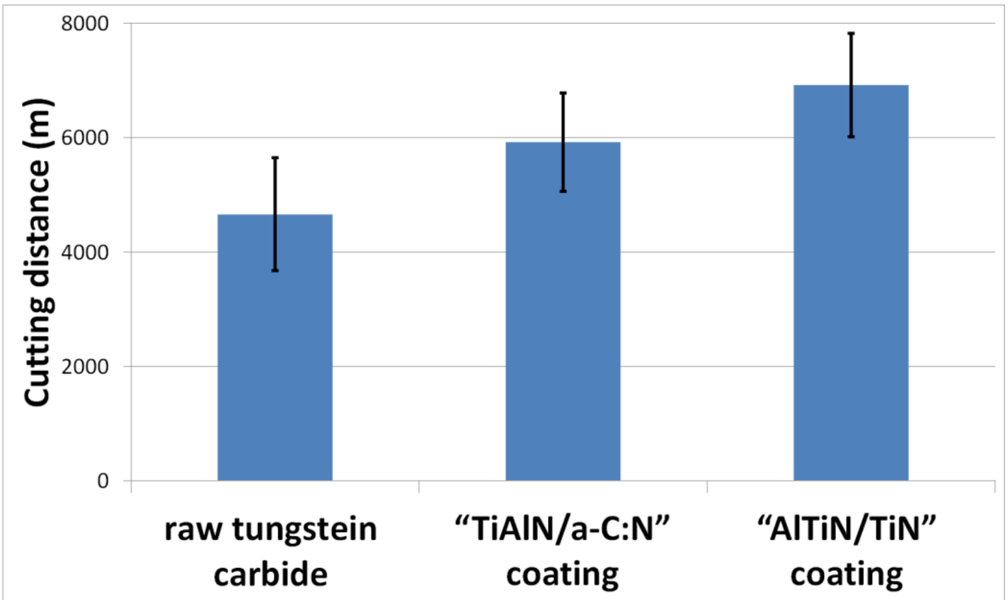


Figure 17. The effect of the 5 µm thick coating on the cutting distance needed for the milling tool wear VB = 0.2 mm [8].

Based on all these data (Figures 14 and 17), it can be concluded that (regardless of whether a drill or a milling cutter was used) the "TiN/AlTiN" coating is far more effective than the “TiAlN/a-C:N” coating. However, additional research is needed to clarify this issue.

4. Conclusions

The experimental research results can be the basis for the following conclusions.

1. The durability of standard (raw) tungsten cemented carbide K05 turned out to be more uniform (more reproducible) than the durability of the tested PVD coatings (“TiN/AlTiN” and “TiAlN/a-C:N”). This was a completely unexpected but clear drawback of using these coatings, especially “TiAlN/a-C:N”. The conclusion came from the analysis of the correlation between the wear of two blades used in the same two-blade drill. The fact that both these blades were cutting essentially the same material was very important because this circumstance reduces the effect of the unavoidable and random variation in the properties of the material that was drilled on the variation in tool wear. This correlation turned out to be the highest (with the coefficient of determination of R^2 = 0.85) in Group A, which was the control group containing unmodified tools (the blades of these tools were made of raw tungsten cemented carbide K05). The lowest correlation (R^2 = 0.59) was in Group C, which was the experimental group containing tools coated with “TiAlN/a-C:N”). For Group B (the experimental group containing tools coated with “TiN/AlTiN”), the coefficient of determination was rather moderate (R^2 = 0.74) but smaller compared to the control group.
2. The advantage (greater resistance to wear) of both tested coatings (“TiN/AlTiN” and “TiAlN/a-C:N”) over raw cemented carbide was statistically significant in the initial phase of machining (before 800 holes were drilled). This statistical significance was verified by standard analysis of variance (one-way ANOVA).
3. Unfortunately, in the final phase of machining (when the number of holes drilled was over 800), only one coating (“TiN/AlTiN”) retained its advantage over raw cemented carbide. The effect of the second coatings (“TiAlN/a-C:N”) turned out to be statistically insignificant.
4. In general, the results of the experimental study confirmed the conclusion made in previous research that the “TiN/AlTiN” coating seems to be much more effective than “TiAlN/a-C:N” in the case of woodworking tools.

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