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Hard coatings for woodworking tools – a review

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ABSTRACT

Purpose: The paper presents thorough analysis of the state-of the-art in the field of woodworking tools durability improvement. In comparison with the achievements of global leaders in the field, the technologies developed so far at the Institute of Mechatronics, Nanotechnology and Vacuum Technique, as well as the latest research works undertaken by the authors are presented.

Design/methodology/approach: The specificity of machining conditions of wood and wood-derivative materials consists in simultaneous occurrence of very high working speed, extremely sharp cutting edges and high working temperature – on the one hand, and high anisotropy and low thermal conductivity of the machined material – on the other. The paper summarizes various ways, including selection of both tool materials and surface treatments, applied in order to increase the productivity of woodmachining.

Findings: A systematic analysis has been made on the type of tool materials suitable for machining of different sorts of solid wood and wood-derivative materials. It was shown that all woodworking tool types, except for satellites, require development of dedicated surface engineering technologies improving significantly their durability. The main features of CVD and PVD surface treatment technologies were compared in relation to their application for woodmachining tools.

Research limitations/implications: Based on the achievements to date IMN&VT undertook a project aimed at development of a new generation of surface treatment technologies for both cemented carbide and high speed steel tools. It is planned to develop three packages of PVD technologies for deposition of multilayer and duplex anti-wear coatings based on TiAlN, CrN and carbon.

Originality/value: The paper constitutes concise but in-depth description of the contemporary trends in surface treatment of tools for woodmachining.

Keywords: Surface treatment; Tools for woodworking; Multilayers

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1. Introduction

The machining of wood and wood-derivative materials requires special knowledge on woodworking technology because of their specific properties like: high anisotropy of the material structure, abrupt changes of intrinsic stresses and local hardness (e.g. in laminated materials) and considerable dimensions of machined parts.

The development of tools for cutting wood and wood-derivative materials ran similarly to the development of cutting tools for metallic materials. Tool steels, used at the early phase of that development, were replaced by high speed steels. Further development of wood industry and increasing share of difficult-to-machine wood materials led to wide use of composite materials, based on sintered carbides WC/Co, and finally on polycrystalline synthetic diamond. Composite carbide materials consist of soft binding phase (Co), responsible for elastic bonding of hard tungsten carbide (WC) particles, which enhance wear resistance of the tool. Machining properties of carbide composite based tools are determined by the share and size of carbide crystallites. Versatility of sintered carbide cutting tools consists in the possibility to shape their mechanical, thermal and chemical properties through the change of their phase composition, grain coarseness and deposition of protective coatings.

Steel tools, despite wide use of hard and super hard materials, are still very popular in wood industry. For example, manufacturing of tools like cutters for wood peeling machines, drills, disposable graded plates, band-saw blades etc., from hard or super hard materials instead of low alloyed steels, high speed steels or stellites would be, because of the required tool geometry, technically impossible or uneconomic. The main advantages of steel materials are: relatively low price and easy manufacturing of tools with complex geometries. The hardness of steel materials reaches 900 HV10. Therefore, surface treatment of tools increasing their load bearing capacity and resistance to abrasive and corrosive wear is in wood industry especially justified both technologically and economically. The research works carried out recently are aimed at development of "a perfect woodworking tool material" that would join high hardness with high ductility and would show good mechanical, tribological and thermo-physical properties (e.g. increased thermal conductivity coefficient), what would bring significant increase in the tool durability.

2. Materials and surface engineering technologies used in woodworking tools manufacturing

According to perfectly apt definition of the main challenge in tool industry, given by Dennis T. Quinto in his review published in SVC Bulletin [1], the modern tool cutting edge represents the confluence of achievements in materials science and machining technologies striving for an optimized combination of tool material, hard coating and cutting edge geometry [2-8]. Although Quinto's review concerns machining of metal wokpieces, it contains some general rules and hints, as well as selection criteria of the coating-tool system that may be used for optimization of surface treatment of woodworking tools.

There are some general requirements, which determine successful coating selection for cutting operations. The most important among them, regardless of the workpiece material are: good adhesion to the substrate and between coating sublayers, high wear resistance at working conditions, chemical stability and inertness in relation to the workpiece material, fine-grained microstructure, smooth surface morphology and controlled compressive residual stress. These parameters determine coating exploitation characteristics, but they are in turn controlled by physical properties like chemical composition, crystallographic structure, high temperature microhardness, oxidation resistance, thermal conductivity, which also influence the coating micro-fracture toughness and coating-substrate strain compatibility.

2.1. Specificity of wood machining and applied surface treatment technologies

The specificity of machining conditions of wood and wood-derivative materials consists in simultaneous occurrence of several factors, that are difficult to manage even individually, i.e. [9]:

- application of very high working speed,
- extremely sharp cutting edges of the tools,
- intensive abrasive wear and high working temperature.
- low thermal conductivity and high anisotropy of mechanical properties of the workpiece material,

Because of wide variation in the properties of solid woods and wood-derivative materials, woodworking tools have to be manufactured from different materials that fulfil requirements resulting from given application. In general the types of tool materials currently used have not changed during last decade and these are: hardened alloy steels, high speed steels, stellites, cemented carbides and Polycrystalline Diamond (PCD) [9, 10].

Low alloy steels (e.g. 90CMV8) are used for manufacturing knives for chipping, peeling, slicing and particle-producing machines. Besides wood industry, chippers' knives are also used in pulp industry for cutting and trimming paper. High speed steels (e.g. HSS18) are common materials used for planing and shaping knifes fabrication. Because of the advantageous features of low alloy and high speed steels, *i.e.* relatively low price and easy manufacturing of special knifes, *e.g.* very long (4.2 m), with extremely low wedge angles (16°–20°) or with special complex shapes, they cannot be replaced in many applications by any other harder and more abrasion resistant material like *e.g.* stellites, carbides or PCD [11].

Stellites in spite of possessing relatively low hardness (HV580) among woodworking tools demonstrate low cutting edge recession when machining some special wood sorts, e.g. oil palm, which contain silica accumulation species that seem to have significant effect on the intensive wear of HSS tools [12]. A novel technique for bandsawing, which uses a tip-inserted saws with stellite inserts, is gaining increasing popularity.

Among superhard tool materials the most common are cemented carbides, which compared with PCD exhibit higher wear resistance at lower manufacturing costs. Besides, cemented carbide tools can be manufactured with lower wedge angles

(45°–55°) in comparison to PCD tools. Low wedge angles are necessary for machining massive wood and generally give better surface quality. But the lower the angle the higher the wear. Therefore the performance of hard metal tools with low angles must be improved by deposition of hard anti-wear coatings.

Extremely harsh and variable machining conditions lead to quick wear of the cutting tools – some of them would perform poorly when machining species with low strength properties and yet perform better when machining species with high strength properties [12]. Therefore even the hardest tool materials do not guarantee long, failure-free service of the tool because of their inherent susceptibility to catastrophic failure. Therefore all woodworking tool types, except for stellites, are the object of intensive R&D works aimed at development of dedicated surface engineering technologies improving significantly their durability.

The first technology used for deposition of hard anti-wear coatings was Chemical Vapour Deposition (CVD). Since its introduction more then three decades ago it has advanced from single layer to current multilayer coatings tailored to the particular cutting application. CVD technology has been dominant in cemented carbide tools which tolerate high deposition temperatures – reaching 1000°C. Physical Vapor Deposition (PVD) technology, introduced a decade later, allow to create hard coatings at significantly lower substrate temperatures – below 500°C. PVD technology was first proven on high speed steel tools, it has also found acceptance in a narrow application field, directly relating to wood machining, of interrupted-cut and sharp-edged carbide tools [1]. The comparison of physical properties of PVD and CVD coatings of the same chemical composition show that PVD coatings can be harder, have finer grain size and smoother surface morphology, are crackfree and possess residual compressive stress. These are advantageous features relative to CVD, especially in interrupted cut applications and where sharp edges are required [10,11]. Two advantages are however granted to CVD technology: better coating adhesion due to deeper atomic diffusion into the substrate at high deposition temperature and the relative simplicity of depositing thicker coatings and multilayers that include insulating materials like Al_2O_3.

2.2. Coatings applied on cemented carbide tools

In-depth comparative investigations were carried out for three types of coatings applied to cemented carbide woodworking tools: monolayer diamond coatings, multilayer coatings “metal – tetrahedral amorphous carbon” Ti(Al)/ta-C and composite coatings of titanium carbide and amorphous carbon TiC/a-C [9]. The diamond coatings were deposited with the use of hot-filament CVD, composites TiC/a-C using plasma-assisted CVD (PACVD), which allows for significant decrease of the substrate temperature, and multilayers Ti(Al)/ta-C by laser enhanced pulsed vacuum arc PVD technique [13]. The composite TiC/a-C, with the hardness of 3500 HV, consisted of nanocrystalline TiC and hydrogen containing amorphous carbon a-C. The harder Ti(Al)/ta-C coatings (5000 HV) consisted of a hydrogen-free amorphous carbon layers with a high sp^3 content (70%) and thin interlayer of Ti or Al (30 nm). The grain size of the hardest diamond layers (10000 HV) was determined by the substrate temperature. High substrate temperatures led to coarse-crystalline growth, therefore fine-crystalline diamond films were deposited at a temperature of 750°C. Moreover, at such substrate temperature cobalt diffusion in the layer and following graphitization was avoided.

The wear tests, carried out with the use of the laminated particle board, revealed the dependence of the wear behaviour of the multilayer and composite coatings on their thickness. The TiC/a-C composite coatings showed considerable increase of wear resistance (up to 210%) with lowering the coating thickness – coatings thicker than 3μm did not lead to any improvement in comparison to uncoated tools. Also thin Ti(Al)/ta-C coatings improve the tool performance, moreover the kind of metal interlayer was not important. Both Al/ta-C and Ti/ta-C show nearly the same wear behaviour – these only 0.33μm thick coatings increased the tool lifetime up to 250%.

I. Endler et al. [9] ascribed the worse wear behaviour of coatings thicker than 3μm only to the remarkable increase of cutting edge radius, causing decrease of the cutting edge sharpness with rising coating thickness. It seems that more accurate interpretation of this effect was given by D. T. Quinto [1], who pointed at the U. Wiklund’s research on the role of the residual stress distribution at the “sharp edge”. According to U. Wiklund’s results the residual stress in PVD coatings can exert an unbalanced distribution at sharp discontinuities such as the sharp cutting edges [14]. Therefore the edge sharpness and/or coating thickness should be limited to avoid self-delamination of coating along the edge. Since the residual stress increase with coating thickness, thick PVD coatings are not compatible with extremely sharp edges. This problem is particularly important in the case of woodworking tools.

The wear behaviour of diamond coated tools was to a large extent determined by the coating adhesion. Three methods were applied to improve diamond coating adhesion to cemented carbide substrates: etching of cobalt from subsurface zone, etching of tungsten carbide and deposition of $TiAl_x$ interlayer. Generally, no improvement of tool lifetime was observed for diamond coated tools pretreated by cobalt etching. This was caused by the reduction of the strength of the tool surface zone – the etched substrate could not suport the diamond coating and the tools fail through large delaminations in the wear zone. Substantially better wear behaviour was obtained with the use of the WC etching procedure and $TiAl_x$ interlayer deposition. These two substrate preparation procedures allow to obtain diamond coated tools with remarkably higher performance in comparison with uncoated ones. However, in this case the tool performance was strictly dependent on diamond coating thickness and substrate temperature. Improved wear behaviour could only be reached for a layer thickness below 2μm. In order to obtain the fine-crystalline layer structure and to suppress cobalt diffusion, the substrate temperature should not exceed 750°C.

More recent results point at Cr-based PVD coatings as very effective anti-wear layers for cemented carbide tools. Reported research concerned both binary Cr-N and ternary Cr-Al-N chromium compounds [15, 16].

Binary monolayer CrN and Cr_2N coatings as well as multilayer CrN/Cr_2N coatings were deposited on commercially available carbides of different hardness and tested in milling operation of the oriented strand board (OSB) on an industrial router [15]. The hardness of Cr_xN_y coatings increased significantly with the change of nitrogen content (10%, 20% and 100%) for both mono- and multilayers, but at the same time their adhesion significantly decreased. Moreover the critical load of adhesion was higher and more stable for multilayers than for monolayers. The milling tests proved that the multilayer coatings CrN/Cr_2N turned out to be more wear resistant on softer substrates, while on harder substrates the situation was opposite. On both substrates the decrease of the nitrogen content improved the wear resistance and the adhesion of the coatings.

The deposition of the ternary CrAlN coatings was carried out by a dual RF magnetron sputtering system using pure sintered CrAl target (25% at of Al) [16]. The machining tests were performed using a three-axis industrial route. As a workpiece material medium density fibreboard (MDF) was used. Obtained coatings had hardness of around 20GPa and were well adherent on carbide tools. They were also low stressed and decreased the tools wear, measured after 1700m of routing, by about 250% when compared to unmodified tools.

2.3. Surface treatment of steel tools

The usefulness of Cr_xN_y compounds produced by PVD methods to improve wear resistance of steel woodworking tools was widely investigated. M. G. Faga and L. Settineri studied the effects of application of this type of coatings on high speed steel HSS18, commonly used for planing and shaping knife fabrication, and on alloy steel 90CMV8, used for chipper and canter knife fabrication [10]. For comparison DLC coatings were investigated. Surface modifications performed included: different nitriding processes (at 300°C and at 500°C), application of two types of antiwear DLC coatings (created using RF PACVD and cathodic arc evaporation) as well as chromium nitride monolayers (cubic CrN) and chromium nitride multilayers (cubic CrN/hexagonal Cr_2N) as well as combination of nitriding and coating deposition (duplex coatings).

Machining tests were performed with a vertical milling machine at cutting speed of 1740 m/min and feed rate of 3000 mm/min and included following coating materials configurations:

- nitrided layers created in low- and high-temperature nitriding,
- mono- and multilayer Cr_xN_y coatings deposited by cathodic arc evaporation on unnitrided substrates,
- mono- and multilayer Cr_xN_y coatings deposited by cathodic arc evaporation on substrates nitrided in low- and high-temperature processes,
- DLC coatings created by RF PACVD and cathodic arc evaporation deposited on unnitrided substrates,
- DLC coatings created by RF PACVD and cathodic arc evaporation deposited on substrates nitrided in low- and high-temperature processes.

Surface modified knives with low-temperature nitrided layer, monolayer CrN and DLC coatings and with duplex layers that combine low-temperature nitrided layer with mono- and multilayer Cr_xN_y coatings demonstrated higher cutting performances in comparison to unmodified ones with application to spruce wood in vertical milling operations. The highest cutting efficiency showed monolayer DLC and CrN coatings both deposited by cathodic arc evaporation on unnitrided substrates. Also duplex treated tools combining chromium based coatings with low-temperature nitriding gave significant increase in tools durability. Analysis of the wear morphologies of the knives at the end of the milling tests showed that the uncoated and high-temperature nitrided tools underwent edge failure, whereas the tools coated with CrN and DLC layers exhibited a slow, regular wear. The analysis of fracture phenomena observed on the tested tools unambiguously showed that when the tool surface is too fragile, like in the case of high-temperature nitrided, the high brittleness of the material caused a premature failure of the cutting edge.

2.4. Innovative directions

Coating materials used for woodworking tools must show high hot hardness because at high machining speeds, particularly in continuous cuts, high heat is obtained. The problem of heat concentration at the cutting edge is worst with workpieces having low thermal conductivity and poor transfer of heat to the outgoing chip – just like in the case of wood and wood-derivative materials. In such cases the coating should have good thermal conductivity to dissipate heat away from contact areas of the cutting edge [1]. Therefore at present the R&D works are aimed at development of innovative, multilayer and nanostrutural coatings that would allow to take advantage of high hot hardness of the materials like TiAlN or CrAlN and at the same time would allow to increase thermal conductivity and ductility of the coating.

TiAlN is a very popular coating for high-speed cutting manufacturing processes. Design and production of coatings based on TiAlN with interlayers of metal with low elastic modulus, like Al, Ti or Cu may contribute to improvement of cutting efficiency. Such multilayer, nanometric structures were created by J. M. Castanho and M. T. Vieira [17]. The coatings contained 80 nm thick metallic interlayers (Al or Ti) deposited alternately with TiAlN layers. In general, the hardness and Young’s modulus of such multilayer coatings had slight smaller values, but the H/E relation was the same as in monolithic TiAlN coatings. Moreover, the adhesion showed significant increase with both Al and Ti interlayers, what was considered as an important contribution to the improvement of the cutting performance of TiAlN-based coatings. The coatings were successfully applied on both carbide and HSS tools used for secondary wood products cutting [18].

Similar approach, but with the application of compound interlayers, suitable for dry machining tools was pointed out by D. T. Quinto [1] and consists in deposition of multilayered AlCrN-TiSiN coatings. Although AlCrN has low thermal conductivity the multilayer construction with TiSiN, which has high thermal conductivity, effectively raises the composite conductivity, minimizing the heat concentration at the tool cutting edge.

An emerging new approach to the construction of antiwear coatings, presented by M. Stueber, U. Albers *et al.* [19], is the design of nanocomposite coatings composed of ternary or quaternary metastable hard phases such as fcc (Ti, Al)(N, C) or fcc (Ti, Cr)(C, N) and amorphous carbon [19]. These multilayers are composed of nanometer thin layers of different carbon-based nanocomposite coatings and are by the authors referred to as nanolaminated composite coatings. Nanolaminated coatings with TiC/a-C and (Ti, Al)(N, C)/a-C nanocomposite layers exhibited hardness between 12.5 and 13.5 GPa, which did not vary much with the number of layers of the multilayer compound. The nanoarchitecture of this multilayer coating did not change during annealing in vacuum for 4 h at the temperature of 1000°C and no recrystallisation was observed. This result suggests the existence of very stable grain boundaries in such layers, what makes them very promising candidates for the development of advanced wear-resistant coatings for extremely loaded cutting tools.

3. Surface treatment of woodworking tools at the Institute of Mechatronics, Nanotechnology and Vacuum Technique

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The R&D works in the field of surface treatment of woodworking tools were started in the Institute of Mechatronics, Nanotechnology and Vacuum Technique more then a decade ago. Some results of these works were successfully introduced by IMN&VT to the industrial practice among others by Polish factories FABA Baboszewo [20] (Fig. 1) and GOPOL Jarocin at the beginning of the year 2000.

Fig. 1. The planer knives produced by FABA Baboszewo with the ”Tiger” coatings based on TiAlN [20]

The first stage of R&D works was summarized in the year 2008 by conclusion of the international project within UE programme INTERREG III A [21, 22]. As a result of the project execution two types of multilayer PVD coatings have been developed and implemented in industrial practice: Cr-based coatings and TiAlN-based coatings (Fig. 2).

The multilayer Cr-based coatings were deposited with the use of the cathodic arc evaporation (CAE) technology and consisted of up to 10 sequences of CrN-CrCN. The coatings exhibited nanometric structure – the crystallite size did not exceed 15 nm [23, 24] (Fig.3). The hardness of the coatings was in the range of 22 GPa – 32 GPa, dependently on the carbon content. They also showed good adhesion to HSS substrate (critical load in the range of 60 N – 90 N) and the friction coefficient lower than that of CrN film, as well as very low wear rate in the ball-on disk test. The multilayer TiAlN-based coatings, also deposited by CAE technology, consisted of up to 20 sequences of TiN-TiAlN with TiAlN as the top layer. The coating hardness exceeded 30 GPa and the critical load in the scratch-test at HSS substrate was higher then 80 N.

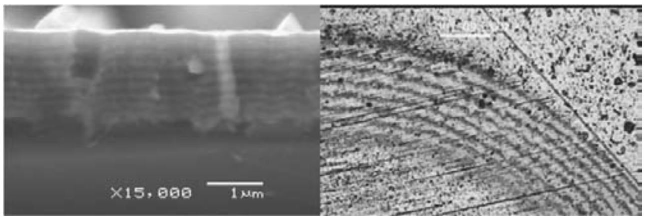
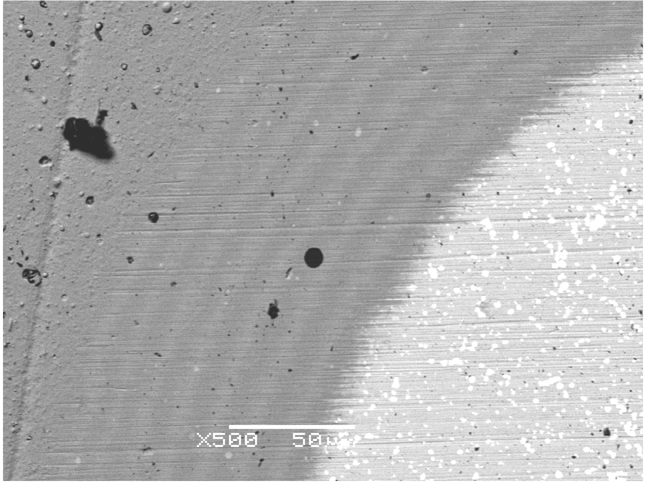


Fig. 2. Fracture cross section and calotest friction track of the TiAlN/CrN coating [22]

a)



b)

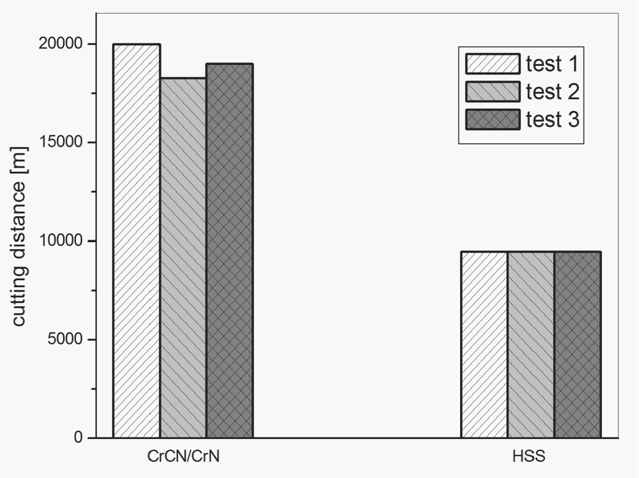


Fig.3. Calotest friction track of the CrCN/CrN coating (a) and the results of cutting tests (b) [24]

Both types of coatings have been implemented in industry on planing and cutterhead knives made of high speed steel (Fig. 4). The tools with CrN-CrCN coatings were used for machining solid wood, while those with TiN-TiAlN coatings for machining oriented strand board (OSB) and medium density fibreboard (MDF). For developed and implemented technologies the Institute of Mechatronics, Nanotechnology and Vacuum Technique was rewarded with prestigious prize "West-Pomerania Nobel 2008" and with the Gold Medal Nomination at the International Fair of Machines and Tools for Wood and Furniture Industry "DREMA 2009" in Poznań.

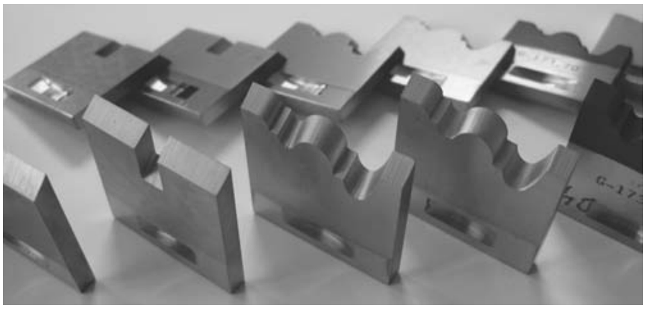


Fig. 4. The tools for wood machining with CrN-CrCN and TiN-TiAlN coatings deposited in the Institute of Mechatronics, Nanotechnology and Vacuum Technique

The present – second stage of R&D works carried out in the Institute on surface treatment of woodworking tools have been started in the year 2009 by the kick-off of the developmental project within the governmental Operational Programme Innovative Economy POIG 2007-2013 [25]. The concept of the project is based on the Institute's achievements to date and is aimed at development of a new generation of surface treatment technologies for both cemented carbide and high speed steel tools. In order to assure the extensiveness required with regard to diversity of wood sorts (hard, *e.g.* beech, oak; soft, *e.g.* pine, spruce) and its different moistness (so-called wet and dry wood) it is planned to develop three packages of PVD technologies for deposition of the following types of multilayer and duplex anti-wear coatings:

- based on titanium-aluminium nitride (TiAlN),
- based on chromium nitride (CrN),
- based on carbon (C).

The main aims of the undertaken project are formulated as follows (Fig. 5):

1. Development of the surface treatment technology of high speed steel woodworking tools that will ensure their superiority over unmodified HSS tools and will allow at least to equalize the durability of modified HSS tools with that of unmodified carbide tools at lower market prices.
2. Development of the surface treatment technology of cemented carbide woodworking tools that will allow to reach the durability comparable with that of PCD tools at significantly lower market prices.

It is assumed that the above formulated aims will be reached with the use of the cathodic arc evaporation (CAE) technology and its combination with plasma nitriding technology (for HSS tools).

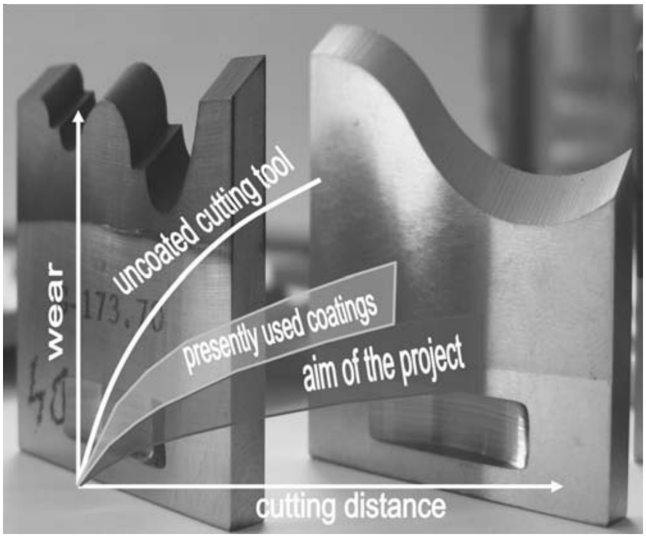


Fig. 5. The aim of the Developmental Project No. UDA-POIG.01.03.01-32-052/08-00: „Hybrid technologies for woodworking tools modification"

4. Summary

The machining wood and wood-derivative materials belong to the most harsh cutting operations. Full exploitation of the technical parameters and the productivity of contemporary woodworking machines as well as meeting market requirements concerning production quality are impossible without tools with modified surfaces. At present, practically all materials used for woodworking tools manufacturing require sophisticated surface treatment. Further improvement of wood and wood-derivative materials machinability will be limited by the ability to adapt recent achievements in materials science in the applied surface treatment technologies.

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