AN OVERVIEW OF DLC COATINGS ON CUTTING TOOLS PERFORMANCE

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ABSTRACT: This paper presents the state-of-the-art and requirements for manufacturing applications of DLC coatings. DCL (*diamond-like carbon* or *amorphous carbon*) thin films on cutting tools bring considerable benefits during chip removal processes. Experimental studies on DLC coated tools used during different cutting operations on different workpiece materials showed that, in most cases, DLC films increased tool life, facilitated chip evacuation and allowed dry machining. Unfortunately, limited adhesion of films on tool surface prevents extending the use of DLC coated tools for hard materials or for discontinuous machining. Nowadays, the major challenges for specialists are to develop new depositing techniques for DLC films and to find the most appropriate machining conditions.
KEY WORDS: DLC, amorphous carbon, thin films, coated tools, tool life.

1 INTRODUCTION

The development of coatings on cutting tools and machine parts began half a century ago as a response to the necessity of increasing wear resistance.

DLC is the abbreviation for *diamond-like carbon*, a material that has similar tribological, mechanical and optical properties to diamond but is considerably cheaper to obtain. DLC coatings are thin films with thickness at micro or nanoscale. DLC films may be deposited at low temperature by two techniques: PVD (Physical Vapour Deposition) and CVD (Chemical Vapour Deposition) on almost any kind of material.

The term of *diamond-like carbon* is commercially attractive revealing the similarities of this material with diamond. Yet, some specialists prefer the term *amorphous carbon* to avoid confusion with diamond which has a crystalline structure. From this point o view, amorphous carbon is superior to diamond, with a higher strength and an amorphous structure lacking fracture plans.

Amorphous carbon films have a large range of applications: in automotive and manufacturing industry, for coating magnetic storage devices, for biomedical use (implants and stents) and optical applications (sunglasses, ophthalmic lenses, etc.).

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In a recent report on coating products is showed that the global market for diamond and diamond-like coatings is estimated at $905 million in 2010 and has a forecasted growth rate about 14% over the next 5 years.

The amount of diamond-type bonded carbon (sp^3), graphite-type bonded (sp^2) and elements like hydrogen, metals or non-metals give the hardness, strength and other properties of amorphous carbon films. Diamond-like carbon has various forms (Figure 1) closer to diamond or closer to graphite according to their composition.

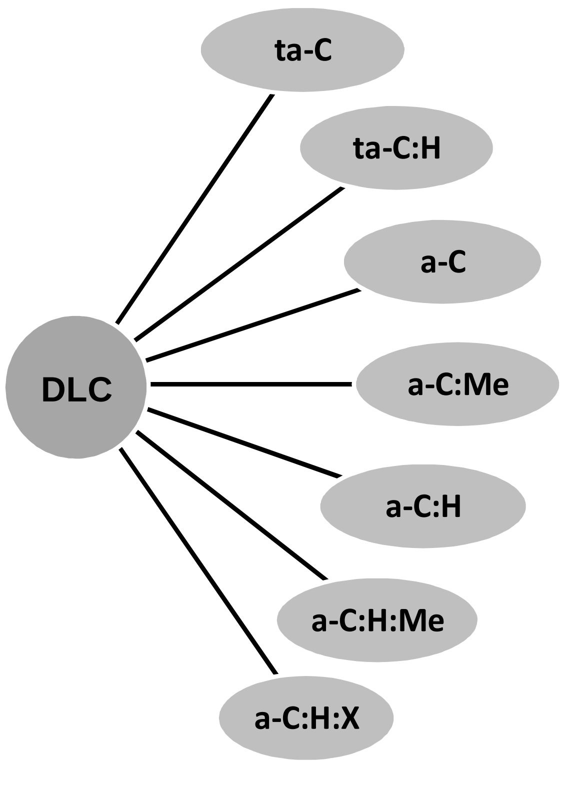

Figure 1. Amorphous carbon forms

The classification of amorphous carbon forms in seven major categories differently symbolized facilitate identifying them:

- **ta-C** is tetrahedral-bonded hydrogen-free amorphous carbon and is the hardest form of DLC having more than 80% sp^3 bonded carbon atoms;
- **ta-C:H** is tetrahedral-bonded (sp^3-bonded) amorphous carbon containing hydrogen;
- **a-C** refers to hydrogen-free amorphous carbon, it has mostly sp^2 bonded carbon;
- **a-C:Me** is hydrogen-free amorphous carbon doped with metals like W, Ti;
- **a-C:H** is the symbol for amorphous hydrogenated carbon;
- **a-C:H:Me** metal-doped hydrogen-containing amorphous carbon (Me = W,Ti);
- **a-C:H:X is** modified amorphous carbon containing hydrogen and non metallic elements (X = Si,O,N,F,B).

The higher is the content of sp^3 bonding in amorphous carbon, the closer to diamond are DLC properties. In Figure 2, are represented the bonds of carbon atoms in diamond, graphite and DLC.

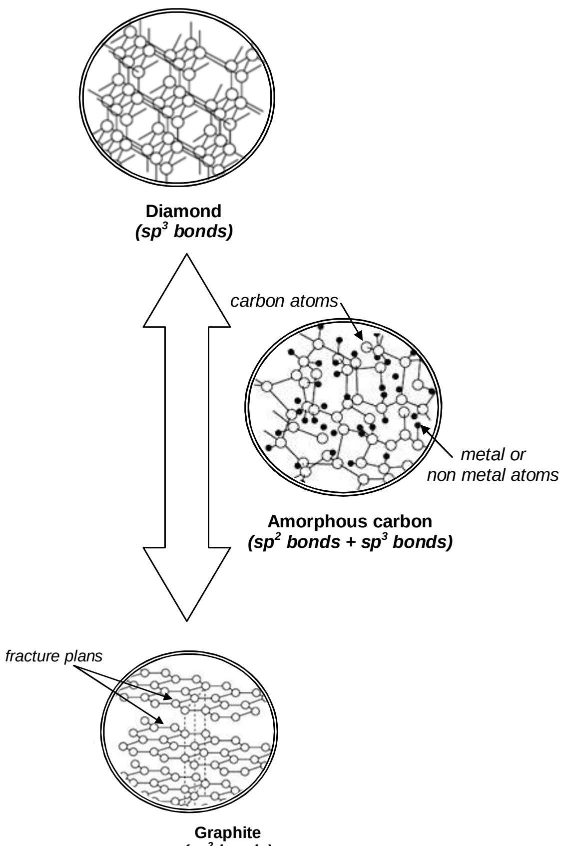

Figure 2. Crystalline structure of amorphous carbon

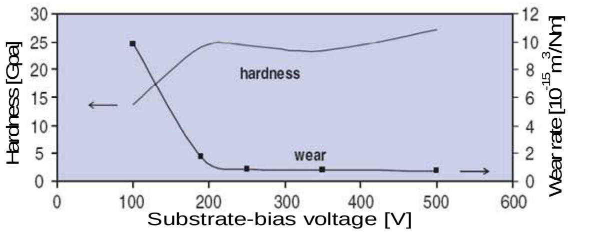

Figure 3. Influence of biais voltage on hardness and wear rate

Deposition methods are continuously improved to produce amorphous carbon with increasing content of sp^3 bonded carbon. For instance, it was proved that a negative voltage at the substrate table (biais) during deposition, favours forming sp^3 bonds and increases hardness and density of the DLC film as shown in Figure 3.

2 GENERALLY USED COATING MATERIALS

Tool manufacturers have a wide choice of common and new coating materials, from traditional coating to more recent multilayer coatings. Among most commonly used coating films are carbon-based (diamond and diamond-like) materials, carbides, nitrides and multilayered coatings.

Diamond is the hardest natural material known by now. Polycrystalline diamond (PCD) may be deposited in micro or nano-layers and increase spectacularly wear resistance. Its deposition requires very high temperatures and pressures. In manufacturing, DLC films have proved to be excellent tool coatings for machining non-ferrous metals, non-metal materials and composite materials. DLC films have high hardness (above 1500 HV), low friction coefficient (less than 0.2) and thermal stability between 400 and 700°C.

The main inconvenient of DLC coating on cutting tools is the adhesion of the film during cutting process. During machining hard materials or during discontinuous processes like milling, nanofilms are peeled off soon after the beginning of the operation. Researchers focus on finding depositing conditions that ensure good adhesive strength and prevent delaminating during cutting process. Some specialists recommend an intermediate layer Si, Ti, Zr, W, Nb, Cr or WC between tool material and DLC layer to improve adherence.

Among nitrides titanium nitride (TiN) is the most used tool coating. It has hardness, toughness, inertness and good adhesion to substrate.

Other nitrides are chromium nitrides (CrN), zirconium nitride (ZrN) and cubic boron nitrid (c-BN). The cubic boron nitride is second hardest material after diamond, but has adhesion problems and production costs are high.

Titanium carbo-nitride (TiCN) is a thin film coating developed from Titanium Nitride. It has better wear resistance, but has lower temperature resistance.

Carbides are also common coating materials that increase tool life at reasonable costs. Beside titanium carbide (TiC) are used chromium carbide (CrC), silicon carbide (SiC), tungsten carbide (WC), vanadium carbide (VC) an boron carbide (BC).

Carbon nitrides coatings (CN_x) are superhard coatings expected to be even harder than diamond as studies predicted.

Multilayered coatings include two (binary coating like TiC/TiN, TiC/Al2O3, etc.) or many stacked films (multi-component coating like CN/TiCN/TiN, TiN/TiCN/TiC or TiAlN/CrNx). Graded coatings are multi-component coatings that have a continuous variation of concentration of components in the film and better adhesion.

Progress in coating materials will continue to accelerate and superior materials or new deposition techniques will be developed. Selecting the best coating and its deposition process is complicated since the number of coating materials, their combinations, and fabrication methods are constantly increasing. Tool suppliers' success on the market will be decided by economical and environmental criteria.

3 TOOL COATING REQUIREMENTS

3.1 Manufacturing process

Improving performances of manufacturing process is possible only with the combined efforts of manufacturers and tools suppliers. End-consumers are more and more demanding and competition on a global market is fierce. Cutting tool manufacturers must take into account every aspect of manufacturing as in Figure 4:

- workpiece,
- cutting tool
- cutting process.

3.2 Tool coating films properties

Corroborating all the aspects related to manufacturing, it can be established a list of expectations for tool coatings. Films deposited on tools should meet the following requirements:

- decrease friction coefficient between tool and workpiece;
- preserve the geometry of cutting edge during machining;
- increase tool life by reducing wear;
- ensure good surface roughness and high accuracy of workpiece;
- decrease cutting force;
- improve fracture resistance;
- prevent workpiece material to stick on tool tip;
- allow manufacturing without lubricants or with minimum quantity of lubricants (MQL);
- increase tool thermal resistance;
- having high-adhesion on tool material or on intermediate layer;
- having low thermal conductivity;
- having a high chemical stability.

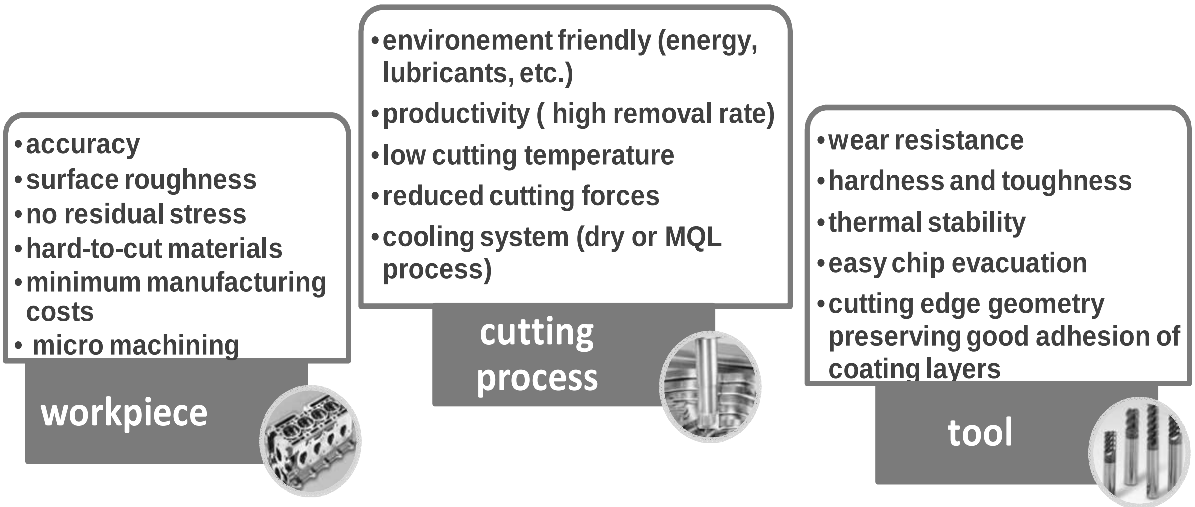

Figure 4. Challenges in manufacturing process

Coating films are applied to all kind of cutting tool materials: high speed steels, tungsten carbides, ceramics and even cermets.

Among other tool coatings, amorphous carbon or DLC satisfy the most of requirements listed before and can be deposited on all types of tool materials, except high film adhesion. DLC coatings combine excellent tribological properties, electrical properties and chemical properties with mechanical properties. Applied on inserts, end mills, and drills, the DLC tools are environmental friendly allowing dry cutting and semi-dry cutting.

Many studies on DLC films cutting performances led to different results showing an important dependence on the quality of the coated tools, the cut materials and cutting parameters and conditions. A review of recent literature reveals that most papers are focused on continuous machining processes of aluminium, bronze and composite materials. It was difficult to find articles on DLC applications for interrupted machining processes or for steel workpiece.

4 DLC COATING PERFORMANCE IN MACHINING PROCESSES

4.1 DLC films tests during turning

A Brazilian team studied DLC coating on cemented carbide tools used in turning Al-Si alloys. They made a series of film measurements and determinations during turning:

- hydrogen content of DLC film
- film thickness
- film's mechanical properties (nanohardness, Young modulus)
- friction coefficient between tool and workpiece
- cutting force
- tool wear

Since this paper aims to describe the behaviour of DLC coatings during cutting processes, turning test conditions are listed in Table 1:

Table 1. Al-Si turning conditions

Characteristics/ Parameters		Description/ Value
Tool material (film substrate)		Cemented carbide
Film thickness		2.5 µm
DLC coating		type a-C:H
Tool/film interlayer		CrC/Cr
Workpiece materials		Al-Si alloy (12% Si)
		Al-Si alloy (16% Si)
Cutting parameters	Cutting speed	450 m/min
	Feed rate	0.15 mm/rev
	Cutting depth	0.5 mm
Cooling system		dry

The results of the study, led to following observations:

- workpiece Al alloy with higher silicon content (12%) adhered more on the DLC coated tool;
- for both worpiece material cutting forces were slightly lower for DLC coated tools than for uncoated tools, decreasing with 4-6%;
- tool wear on coated tools appeared because aluminium was welded on tool tip and the fact that DLC was stripped off.

These conclusions are in concordance with previous studies of Chinese experts on Al-Si alloys. Cutting conditions of their tests are presented in Table 2:

Table 2. Al alloys turning conditions

Characteristics/ Parameters		Description/ Value
Tool material (film substrate)		Cemented- carbide
Film thickness		10 µm
Workpiece materials		Mid Si alloyed Al-Si
		Al-22% Si alloy
		Aluminium bronze
Cutting parameters	Cutting speed	113-220 m/min
	Feed rate	0.1-0.21 mm/rev
	Cutting depth	0.5- 4.25 mm
Cooling system		dry

After testing all three materials, Chinese team also found no improvement in using DLC coatings for turning mid alloyed Al-Si. Instead, when turning aluminium bronzes and high Si alloyed aluminium alloys (Al-Si containing 22% Si) wear rate decreased significantly. Tool life was seven times higher for aluminium bronze and 27 times higher.

It may be assumed that hard Al alloys are more suitable for turning with DLC coated tools.

Other researchers published the results of testing DLC during turning composite materials. CVD technique was used for DLC films on tungsten carbide tools. In Table 3 are described manufacturing conditions of their tests on glass fibre reinforced plastics (GFRP):

Table 3. Composite turning conditions

Characteristics/ Parameters		Description/ Value
Tool material (film substrate)		(WC-Co)
Film thickness		10 µm
DLC coating		CVD
Workpiece material		GFRP (75% fibre)
Cutting parameters	Cutting speed	250 m/min
	Feed rate	0.1mm/rev
	Cutting depth	1 mm
Cooling system		dry

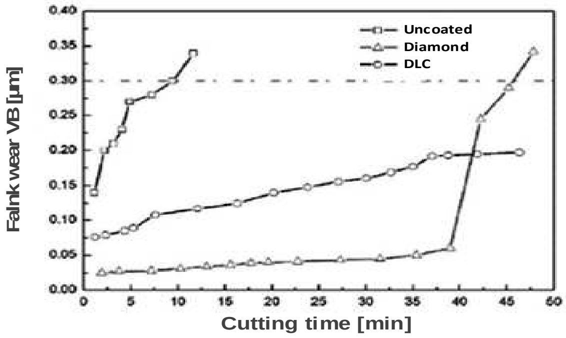

Figure 5. Toolwear comparison

Measures of flank wear on uncoated tools, diamond-film coated tools and DLC coated tools, showed that the latter have the longest tool life (Figure5). After machining about 45 min, diamond tool surpassed VB=0.3 µm limit, while DLC tool had a flank wear less than 0.2 µm. Also, friction coefficient was lower and chip evacuation was better when turning GFRP using diamond and diamond-like coated tools.

4.2 DLC films tests during milling

Milling is the most used cutting operation and the less studied from DLC coating on tools. Being an interrupted process, chip removal is more difficult and thin films do not resist long time.

Fukui and his colleagues performed end-milling test on aluminium alloy with DLC coated and uncoated mills.

The experiments showed a better surface finish in case of DLC coated tool (Figure 5), lower friction coefficient (0.1) and excellent anti-adhering property against workpiece material.

Chip evacuation was easier and chip length decreased with 37 % (from 5mm to 8mm) when using DLC tool.

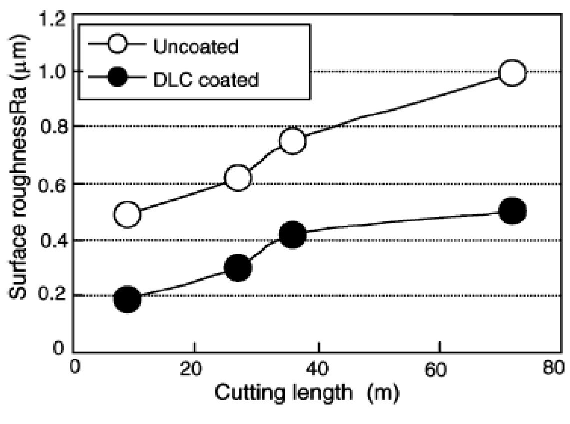

Figure 6. Milling surface roughness for DLC coating

Table 4. Al alloy end- milling conditions

Characteristics/ Parameters		Description/ Value
Tool material (film substrate)		Cemented-carbide (K20)
Film thickness		0.1 µm
DLC coating		type ta-C
Tool diameter		32 mm
Workpiece material		AlMg2.5
Cutting parameters	Cutting speed	300 m/min
	Feed rate	0.15 mm/rev
	Cutting depth	1 mm
	Radial depth	5mm
Cooling system		dry
		wet (26 l/min)

DLC coated inserts had very little built-up edge and preserved longer the geometry and sharpness of the tool. Cutting force decreased by using DLC coating from 600 N to 325 N under dry conditions and from 538 N to 253 N under wet conditions.

More recent studies on face milling aluminium alloys with DLC coated tools, showed that using lubricants reduces considerably Al tendency to weld on cutting tool.

Machining conditions were also improved by texturing rake face of the mill in order to retain lubricant and reduce friction. Nano- and micro-grooves were laser developed on two directions: parallel and orthogonal to cutting edge.

Parallel texture had the best adhesion resistance to workpiece material on tool during milling. Grove direction did not influence the friction on rake face. Calculated after cutting force measurements, in both cases –parallel and orthogonal grooves- the friction coefficient was almost the same.

Both factors, cooling liquid and texturing rake face, decreased build-up edge to extreme low values (0.5µm after milling length of 1800m). In Table 5 are listed manufacturing conditions during tests.

Table 5. Al alloy face- milling

Characteristics/ Parameters		Description/ Value
Tool material (film substrate)		Cemented carbide
Film thickness		0.8 µm
Coating		Tungsten interlayer / DLC
Tool diameter		80 mm
Workpiece material		Al alloy (A5052)
Cutting parameters	Cutting speed	380 m/min
	Feed rate	0.12 mm/rev
	Cutting depth	3 mm
	Radial depth	< 80mm
Cooling system		wet (12.6 l/min)

4.3 DLC films tests during drilling

4.3.1 DLC coated tools for conventional drilling

Japanese scientists tested carbon-based multi-layer coatings for drills. They developed two binary coatings of crystal diamond and DLC above. First coating had a CVD diamond layer with coarse grain (conventional diamond) and a DLC layer deposited on it. Second coating had the DLC film put on fine crystal diamond layer instead of conventional diamond layer. Drilling tests were done with four versions of coatings on carbide drills:

- single layer of fine diamond coating;
- double layer containing a conventional crystal diamond film and a DLC film above;
- double layer of fine crystal diamond film directly on tool and DLC film;
- uncoated tools for reference.

Cutting parameters are mentioned in Table 6.

Table 6. Al alloy drilling conditions

Characteristics/ Parameters	**Description/ Value**	
Tool material	Cemented tungsten carbide	
Film thickness	0.8 µm	
Tool diameter	6 mm	
Workpiece material	Al-Si alloy with 12% Si	
Multilayer coatings	Conventional diamond + DLC	
	Fine crystal diamond + DLC	
Cutting parameters	Cutting speed	85 m/min
	Feed rate	0.12 mm/rev
	Cutting depth	18 mm
Cooling system	MQL (10 l/h)	

After measuring friction coefficient, a hierarchy of coatings was established from tribological point of view: the best coating was DLC on fine crystal diamond, then followed by the fine crystal diamond single layer and then by DLC on coarse grain diamond.

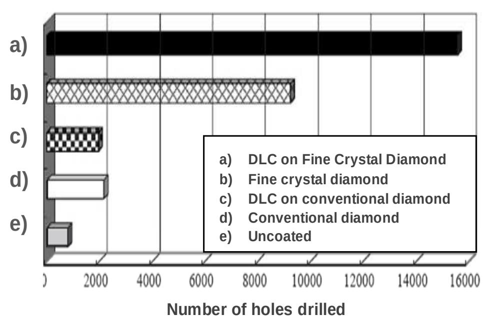

Figure7. Tool life of carbon based-coated drills and uncoated drills

Tool life was estimate by the number of identical holes drilled with every tool before worning out. As shown in Figure 7, multilayered DLC/Fine crystal diamond coating is far the most wear resistant, its tool life is 15 times greater than uncoated drills tool life.

4.3.2 DLC coated tools for deep drilling

It is considered deep drilling if the hole has a ratio of depth vs. diameter superior to 5. Cutting process is difficult because of difficulty of chip formation and removal, high temperature in the cutting zone.

Critical wear determine tool deviation from the axis of the hole or even tool breakage. Low friction coefficient between DLC and workpiece material could theoretically improve chip evacuation. However, experimental study of deep drilling in plain carbon steel showed that DLC is not suitable for deep holes.

Table 7. Carbon steel deep drilling conditions

Characteristics/ Parameters	**Description/ Value**	
Tool material s	HSS	
	Co-HSS	
Film thickness	2-2.7 µm	
Drill diameter	1.5 mm	
Cutting lenhgt	15 mm	
Coatings	DLC type a-c:H:X	
	MoS_2	
	TiN	
Workpiece material	Plain carbon steel	
Cutting parameters	Cutting speed	26 m/min
	Feed rate	0.26 mm/rev
Cooling system	MQL (18ml/h)	

Deep holes of 15 mm length were machined with 1.5 mm diameter coated and uncoated tools. Different coating materials were used: amorphous carbon (DLC), titanium nitride (TiN) and molybdenum disulfide (MoS_2) for drills. Test results showed that DLC-coating reduced tool life with 10-15% compared to uncoated drills. On the contrary, MoS_2- coatings and TiN coating improved tool life with 7%, respectively 32%.

4.3.3 DLC coated tools for micro drilling

Although there is no consensus between specialists on the limit between drilling and micro drilling, it is generally accepted that “micro drilling” refers to drilling with diameters less than 1mm. For micro drills, tool failure is caused by breakage and not by abrasive wear. DLC coatings reduce flexibility and increase tool life.

Swiss specialists tested innovative DLC nano films on micro drills at very high spindle speeds. Several holes were drilled in 0.4 mm stacked copper clad laminates with 0.1 diameter drills and results showed DLC coating significantly improved tool life. Both at 200000 rev/min spindle speed and at 300000 rev/min spindle speed, tool life of DLC coated drills was 7 times higher than in case of uncoated tools.

5 CONCLUDING REMARKS

Experimental studies revealed that using DLC coated tools during machining aluminium alloys and composites is highly beneficial. DLC films prevent adhesion of aluminium on tool, decrease cutting forces, improve machined surface roughness and accuracy, facilitate chip evacuation and significantly reduce wear.

In case of deep drilling carbon steel, the use of DLC coated tools seems not to be justified. Instead, DLC coatings on tools for micro drilling proved to be very promising. Cutting performance of DLC coated tools is insufficiently evaluated and under-potential exploited by now. More studies must be focused on cutting performance of DLC tools for steel and harder materials.

Since new CVD and PVD deposition methods continue to be developed, obtaining DLC film with better adhesion on tools is just a matter of time. Beside technical aspects, environmental factors and economic factors will make the difference in tomorrow's manufacturing.

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7 NOTATION

The following symbols are used in this paper:
DLC = diamond-like carbon / amorphous carbon;
HSS = High Speed Steel;
PVD = Physical Vapour Deposition
CVD = Chemical Vapour Deposition
MQL = Minimum Quantity of Lubricant
GFRP = Glass Fibre Reinforced Plastics.