THESIS ON MECHANICAL ENGINEERING E66

Performance of Tool Materials in Blanking

ALEKSEI TŠINJAN

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DEPARTMENT OF MATERIALS ENGINEERING

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Supervisor:

Professor, Jakob Kübarsepp, Department of Materials Engineering, Tallinn University of Technology

Advisor:

Dr., Heinrich Klaasen, Department of Materials Engineering, Tallinn University of Technology

Oponents:

Professor Michal Besterci, Institute of Materials Research, Slovak Academy of Sciences, Slovak Republic

Professor Priit Kulu, Department of Materials Engineering, Tallinn University of Technology

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Tallinn University of Technology
Ehitajate tee 5, Tallinn

Declaration:

Hereby I declare that this doctoral thesis, my original investigation and achievement, submitted for the doctoral degree at Tallinn University of Technology has not been submitted for any academic degree.

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MEHHANOTEHNIKA E66

Tööriistamaterjalide toimivus väljalõikestantsimisel

ALEKSEI TŠINJAN

TTÜ KIRJASTUS

CONTENTS

FOREWORD

Development of new advanced materials and related technologies is one of the major factors for industrial success. The role of materials technology is to act as technology enabling elaboration of new innovative products and applications. The challenge is to develop new cost-effective and reliable materials on the basis of advanced technologies and to effectively utilize this technology for new commercial products. Virtually all technology forecasts from industry consider ability to produce composites and other multiphase structures economically. Management of life-cycle costs requires a comprehensive basis for material selection, understanding of material degradation (wear, damage and fracture under cyclic loads etc.) mechanisms.

Several tasks of materials technology are related to tool materials utilized in plastic forming of metals, particularly in sheet metal forming. The foundation for the performance of sheet metal forming tools, especially their active elements such as blanking die and punch, is laid during their production. Heat treatment, hard machining (electric discharge machining), finishing (grinding) and coating produce a lasting effect on the properties of these elements (dies, punches) during their service life. The tool designer selects the material for the elements and the hardness required according to the expected stressing. The main factors dictating the choice of hardness are compressive stresses that elements can be subjected to. With elements of metalforming tool exposed to intensive abrasion the content and homogenous distribution of special carbides is crucial. At the same time homogenously distributed carbides provide the necessary base for thin PVD coatings. In considerations of extremely high compressive stresses and abrasion and/or adhesion ceramic-metal composites (WC-Co hardmetal and cermets) can be used.

The current research is related to tool materials utilized in sheet metal blanking. Motivation was to investigate possibilities to increase performance (durability) of sheet metal blanking tools elements (dies, punches) utilizing advanced ceramic-metal composites (TiC-based cermets) and high performance tool steels strengthened by thin PVD coatings.

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And finally, I would like to thank my family for patience.

LIST OF PUBLICATIONS

The present publication is based on the following publications, which are referred in the text by the Roman numerals I – VI.

I Tšinjan, A., Klaasen, H., Kübarsepp, J., Annuka, H., Influence of sintering techniques on the performance characteristics of steel-bonded TiC-based cermets. *Estonian Journal of Engineering*, 2009, 15(4), 283 - 292.

II Klaasen, H., Roosaar, T., Kübarsepp, J., Tšinjan, A., Performance and failure of carbide composites in different wear conditions, *Proc. of European Powder Metallurgy Conference & Exhibition Euro PM2009*, Copenhagen, Denmark, European Powder Association, 2009, 317-322.

III Klaasen, H., Kübarsepp, J., Tšinjan, A., Adoberg, E., Vainola, V., Performance of tool steels strengthened by PVD coatings, *EURO PM2010 Proc.*, Vol 3: EURO PM2010, Florence, Italy, European Powder Metallurgy Association, 2010.

IV Klaasen, H., Kübarsepp, J., Tšinjan, A., Sergejev, F., Performance of carbide composites in cyclic loading wear conditions, *Wear*, 2011, 271, 837-841.

V Tšinjan, A., Klaasen, H., Kübarsepp, J., Adoberg, E., Talkop, A., Viljus, M., Performance of tool steels strengthened by PVD coatings in adhesion and cyclic loading wear conditions, *Proc. of EURO PM2011 Congress and Exhibition*, Barcelona, Spain, European Powder Metallurgy Association, 2011.

VI Kübarsepp, J., Klaasen, H., Tšinjan, A., Roosaar, T., Annuka, H., Wear performance of WC- and TiC-based ceramic-metallic composites, *Proc. of the Int. Conference BALTTRIB'2011*, 2011, 150-155

The author's contribution

The author of this thesis took part in the sample preparation routine. Also he carried out experiments collected, processed and further analyzed the experimental data (Papers I – V). The author also took part in the discussion on the content (of the current thesis) (Paper I – V) and participated in compiling of manuscripts (paper I – VI). The intellectual merit which is the result of the framework where the contribution of every author of related papers should not be underestimated.

APPROBATION AT INTERNATIONAL CONFERENCES

1. Conference "Friction, Wear and Wear Protection", DGM, Aachen, Germany, 2008.
2. European Powder Metallurgy Conference & Exhibition Euro PM2009, Copenhagen, Denmark, 2009.
3. Int. Baltic Conference Baltmattrib 2009, Tallinn, Estonia, 2009.
4. European Powder Metallurgy Conference & Exhibition Euro PM2010, Firenze, Italy, 2010.
5. European Powder Metallurgy Conference & Exhibition Euro PM2011, Barcelona, Spain, 2011

ABBREVIATIONS, TERMS AND SYMBOLS

Abbreviations

ASTM – American Standards for Materials Testing
CVD – Chemical Vapor Deposition
CWTS – cold work tool steel
HIP – Hot Isostatic Pressing
HP – Hot Pressing
GEHIP – Glass Encapsulation Hot Isostatic Pressing
HRA – Rocwell hardness, scale A
HRC – Rocwell hardness, scale C
HSS – High Speed Steel
HV – Vickers hardness
MRR – Material removal ratio
PM, P/M – Powder metallurgy
PVD – Physical Vapor Deposition
SEM – Scanning Electron Microscope
Sinter/HIP – Pressure Assisted Sintering (Overpressure sintering)
XRD – X-ray Diffraction

Terms and symbols

E – modulus of elasticity (Young's modulus)
H – depth of groove measured from cutting edge
L_1, $L_{0.3}$ – adhesive wear resistance (length of cutting path in adhesive wear tests)
N – number of cycles (in blanking and fatigue tests)
N/Δ – wear resistance of blanking die (lifetime in strokes per 1 mm of side wear)
R_{TZ} – transverse rupture strength
R_m – tensile strength
$R_{p0.2}$ – yield strength
A – ultimate elongation
v – cutting speed
h – height of wear land (in adhesive wear tests)
ΔV – volumetric wear rate
ρ – density
R_a – surface roughness parameter (arithmetic values of absolute values)
R – stress ratio (in fatigue tests)
f – frequency (in fatigue tests)
ΔS – fatigue sensitivity

1 INTRODUCTION

1.1 Blanking process

Stamping (blanking) is the most frequently used of all sheet metal working processes. Conventional blanking is still widely used for low cost production of metal parts that do not require high clearness of stamped edges.

As defined by DIN8588 blanking (stamping) includes all separation processes in which the material is separated between two cutting edges moving in opposite directions. The material is deformed by the cutting edges penetrating from both sides until its capacity to deform reaches the limit and the material fractures. Separation of material occurs mainly as a result of shear stresses.

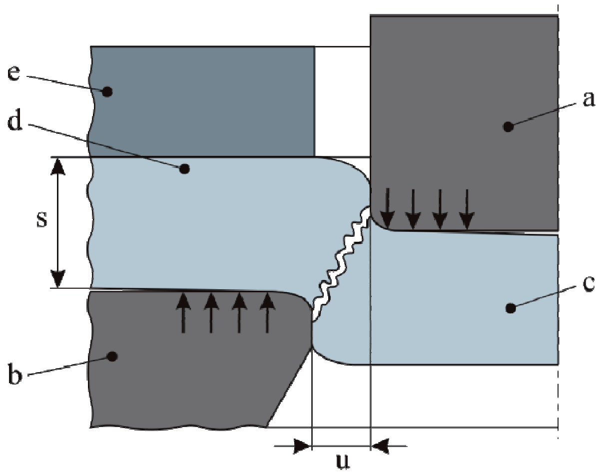

Figure 1 The working principle of the blanking process: a - punch, b – die, c – part, d – work material, e – blank holder, s – material thickness, u – die clearance [1].

The main elements of basic configuration of the tool are the punch, the die (die plate) and usually a blank holder. The scheme of blanking tool is presented in Figure 1. The sheet metal is bed between the punch and the die plate (the "active elements" of the tool) and the parts are sheared out by the downward motion of the punch.

According to [1] separation process of the material can be divided into five phases, during which material undergoes various forms of stressing (Figure 2). The post-flow process can cause wear to the surfaces of both punch and die. Elastic stresses are released when the metal is parted, causing the material to spring back around the cutting edge and changing the dimensions of the part.

This cause jamming of die and can result in abrasive and/or adhesive wear on the sides of the punch and die.

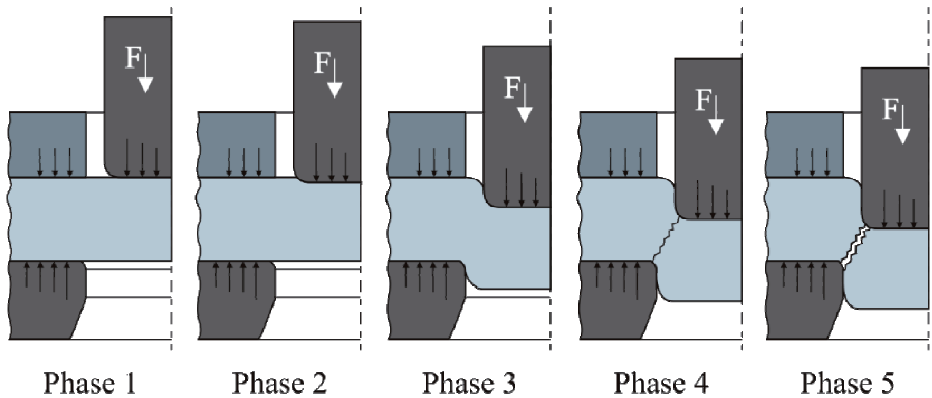

Figure 2 Phases of the cutting process [1]

The quality of the cutting result can be controlled according to DIN 6930 and VDI Guideline 2906 (Figure 3).

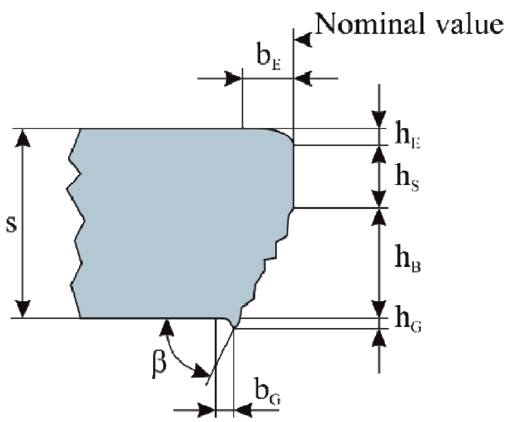

Figure 3 Cut surface characteristic values in stamping [1]

The relevant characteristic values in this connection are:

- die-roll height and width h_E, b_E
- clean-cut zone height h_S
- torn zone height h_B
- height and width of the burr h_G, b_G
- torn taper angle β

These parameters depend as much on the geometry of the punch as on the material properties of the sheet steel. A small cutting edge radius, particularly at the die, usually results in a small burr. A small die clearance also produces a small burr, a low die-roll and a good torn taper angle. Ductile materials have a greater percentage of clean-cut edge than brittle materials [2].

Conventional blanking is a process where clearance between punch and die is about 10-15% of material thickness per side. Therefore blanking tools are under high bending stress in the cutting area which leads to complex stress scheme. The choice of clearance is always a trade off between degree of burring, risk of "shear break" and tool life.

Wear patterns of blanking dies include the following:

a) flank wear can be characterized by length l or area (Figure 4). Flank wear is important because it determines the length that is lost in regrinding. Its origin is in adhesion and abrasion and increases with the number of strokes. The wear length increases asymptotically to the maximum given by the punch penetration;
b) edge (tip) wear, even though difficult to separate from flank wear, is important in that it determinates burr height.

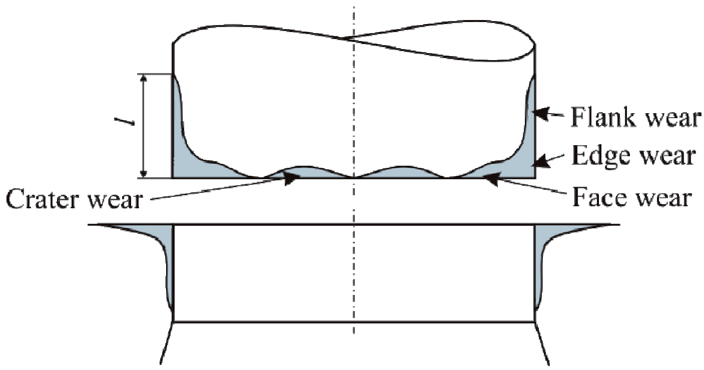

Figure 4 Wear of punch and die [2]

A useful definition for a worn out tool is: "A tool is considered to be worn out when the replacement cost is less than the cost for not replacing the tool" [3].

Blanking application working dies may experience wear characterized by:

- Abrasive and/or adhesive wear resulting in continuous or discontinuous material loss, which is related to sheet material and process conditions;
- Galling due to physical and/or chemical adhesion of sheet material to the tool material. The severity of galling is dependent on surface smoothness, chemical composition of the tool and sheet material and type, size and distribution of hard phases in tool material. Surface coating may reduce or eliminate galling;
- Plastic deformation if working stresses are higher than the compressive yield strength of the tool material;

- Chipping due to the stress from the process and the fatigue resistance of the tool material;
- Cracking due to the stresses in the process, the length and the geometrical configuration of an existing crack result in a stress intensity higher than the fracture toughness of the material.

Adhesive wear is characterized by high wear rates and large unstable friction coefficient. If one surface comes into contact with other, they may adhere strongly and weld to each other. The softer part of material can be then separated (Figure 5). This adhered part can greatly change sliding characteristics of two surfaces. In adhesive wear the surface material properties, atmosphere, as well as possible protecting surface films or contaminants, play important roles [4].

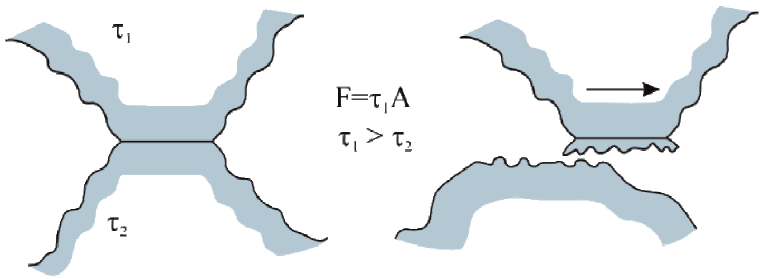

Figure 5 The basic mechanism of adhesive wear [4]

Abrasive wear caused by plastic deformation in a contact, where one surface is considerably harder than the other or where hard particles are introduced as it is shown in Figure 6. The asperities of harder surface deform plastically the softer one resulting in grooves or scratches in the softer material.

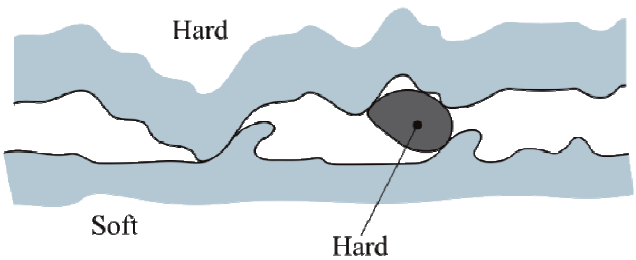

Figure 6 The basic mechanism of abrasive wear [4]

Fatigue wear caused by cyclic loading of the system. Fatigue crack grows during loading and unloading of the surface at a stress level in the material that it can sustain once but not if repeated many times. Fatigue can cause forming wear debris as shown in Figure 7. Contacts between asperities during sliding are accompanied by repeated high local stresses causing fatigue cracks initiation, propagation and fracture [4]. Stresses in the work elements of the blanking tool have variable direction that is more conducing for fatigue wear. The process of debris formation by fatigue wear is described in [5]. The main elements of coating fatigue response as for brittle materials are microstructure and residual stresses. Fine and homogeneous material structures are characterized by slow crack growth [5].

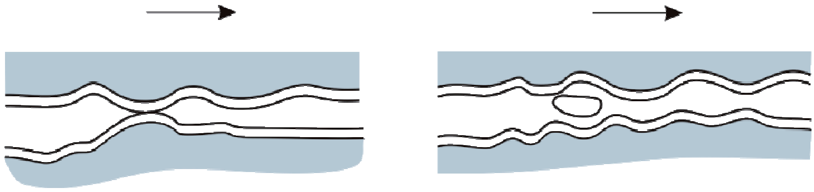

Figure 7 The basic mechanism of fatigue wear [4]

Tool wear can be reduced by using the following approaches:

- selecting a proper tool material for a given application – using of hardmetals and cermets (carbide composites), sintered high-speed tool steels etc;
- increasing hardness of tool surface by treatment (heat treatment, nitriding etc);
- adjusting surface properties (reducing friction coefficient) of tool parts by applying thin coatings: for instance, adhesive wear can be considerably reduced by applying PVD coatings;
- using lubricants and coolants in the interface of tool parts and work material by reducing friction and temperature.

In the present research new tool materials (cermets) and PVD coated high speed steels are utilized for increasing performance of blanking tools.

1.2 Tool materials for blanking tools

The choice of the best material for the metalforming tools must not only take the process into consideration, but also the type of metal being worked and the number of parts to be produced (mass or serial production).

There are some requirements present for working parts (punch and die) of the blanking tool [6]:

- ability of material to withstand great stresses and impact;
- good wear resistance;
- retain sharp cutting edges for possibly long period of time;
- relatively low price of the material and tooling

Dies are subjected to complex stresses and must have fairly high resistance to plastic deformation and brittle fracture, with good wear resistance and toughness. Steels for blanking tools must have high resistance to plastic deformation and good toughness. This combination of properties will retain the shape of the cutting edge for a long time.

Manufacturers of toolmaking materials offer a host of new developments with improved hardening and wearing properties. However, these are not a generally qualified for cutting (shearing) the various grades of high-strength steels. PVD and CVD-based hard material coatings such as TiC or TiN provide an effective means of reducing wear, but the high coating temperatures may warp the tools and possibly influence the hardness characteristics. Sintered high-speed steels and hardmetals even more so have excellent wear properties. On the other hand, these tool materials are substantially more expensive than cold-working steels and can only be repaired or modified to a very limited extent since they cannot be welded [1–2].

Blanking tools are subjected to extremely high-pressure loads and are commonly applied rapidly. The tools must withstand these loads without breaking and without undergoing excessive wear or deformation. No single tool material will provide the maximum wear resistance, hardness, toughness, and resistance to softening at elevated temperatures. The selection of the proper tool material for a given application is often a trade-off. Sometimes more than one grade will provide sufficient results but another grade may provide an optimal combination of properties.

There are three basic classes of tool steels used in metalforming including cold work, hot work and high speed steel. They are categorized by their primary usage. Typically cold work tool steels are suited to applications not exceeding operating temperatures of 250 °C. Hot work tool steels can withstand operating temperature approaching 650 °C. High speed steel (HSS) are a special class with high levels of tungsten or cobalt designed to withstand extreme intermittent operating temperatures usually created by high speed machining operations.

Powder metallurgy (PM) methods allow getting tool steels with enhanced mechanical properties. The disadvantage of HSS of conventional processing is the uneven distribution of carbides in total volume. PM steels don't have the segregation of carbides. Because of reducing the scale of the structure and more uniform carbide distribution, the wear resistance of PM high-speed steels is about 1.5-3 times greater than of conventional ones. Powder metallurgy allow the structure of high speed steel product to be micro-scale graded, it enhance their strength and toughness, and wear resistance. As a result of the finer and more uniform microstructure that PM-HSSs exhibit, as compared to their conventionally produced counterparts, they also present enhanced cross-sectional hardness uniformity (wear resistance), fracture toughness, fatigue strength and superior grindability [7–9].

A blanking tool requires excellent edge retention with good toughness. Toughness in tool steel generally decreases as the hardness increases. Tool steel for blanking (shear cutting) should have a balance between hardness and toughness to withstand cyclic loading stresses and cutting edge chipping.

Table 1 Alloying elements content (%) for selected commonly used metalforming tool steels (Fe – the balance) [6]

Steel Type	C	Mn	Si	Cr	W	Mo	V
A2	1.00	0.90	0.30	5.25	0	1.15	0.30
D2	1.50	0.50	0.30	12.0	0	0.90	0.90
M2	0.85	0.30	0.30	4.15	6.40	5.00	1.90
M4	1.40	0.30	0.30	4.00	5.75	4.50	4.00
Cru-Wear	1.10	0.35	1.10	7.50	1.15	1.60	2.40
CPM9V	1.90	1.30		5.25			9.10
CPM10V	2.45	0.50	0.90	5.25	0	1.30	9.75
CPM15V	3.40	0.50	0.90	5.25	0	1.30	14.50
S390	1.60			4.80	10.5	2.0	5.0
S690	1.33			4.30	5.90	4.60	4.10
Vanadis 4	1.50	0.40	1.00	8.00	0	1.50	4.00

The Table 1 contains some of the commonly used tool steels and their alloy content. While each alloy element listed in the table contributes to a specific characteristic in the finished steel, it also can create an undesirable side effect, particularly when used in excessive amounts.

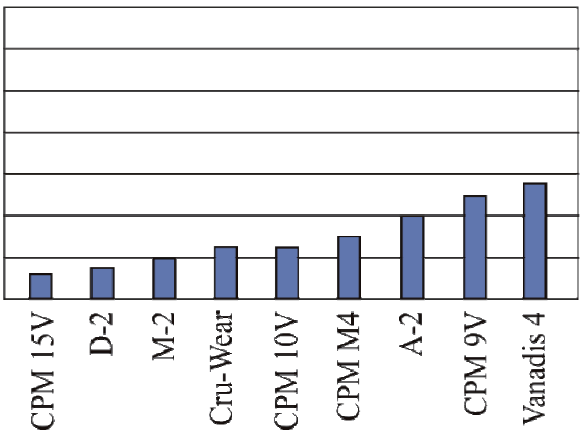

Figure 8 Toughness of selected tool steels [6]

Figure 8 compares toughness of selected tool steels commonly used in blanking (stamping) applications. Tool steel toughness tends to drop as alloy content increases (see Table 1). Higher alloy content also demands a higher price. The steel manufacturing process also effects toughness. The PM process can greatly enhance toughness of a given tool steel grade over its conventional counterpart. Any given grade of tool steel has greater toughness at lower hardness.

Increased alloy content typically means increased wear resistance as shown in Figure 9 (see also Table 1). Increased hardness also adds wear resistance.

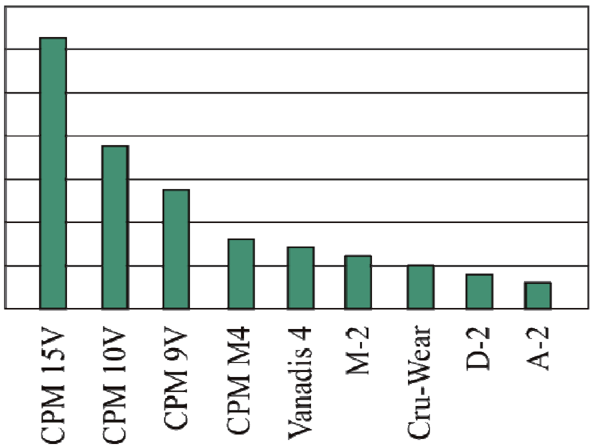

Figure 9 Wear resistance of selected tool steel grades [6]

Application of carbide composites (hardmetals and cermets on basis of carbides) enables the service life of tools and wearing machine parts to be prolonged. These materials are mainly used in service conditions where high wear resistance either in abrasive conditions or at elevated temperature (high-speed cutting operations) is required. Carbide composites, except WC-Co hardmetal, are not so often used in non-cutting (metalforming) operations owing to complicated service conditions, where severe wear is accompanied by high loads of cyclic and dynamic nature.

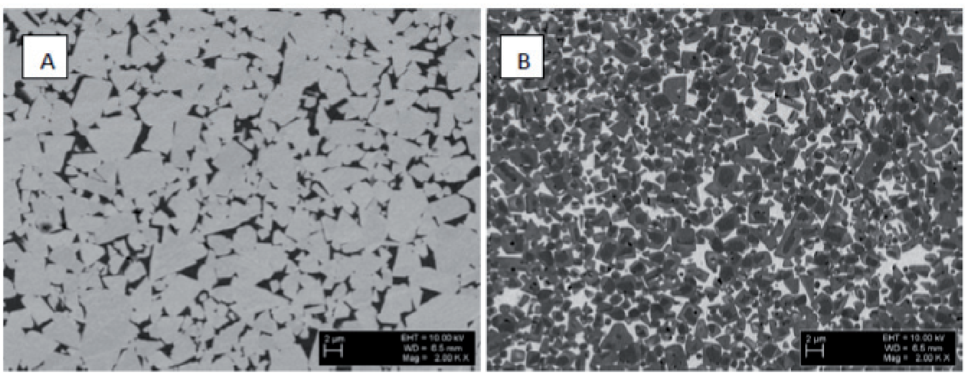

Figure 10 SEM images of carbide composites. A - WC-based hardmetal (WC-15%Co), B - TiC-based cermet (TiC-25%FeNi)

Among carbide composites, hardmetals WC-Co have the most advantageous balance of the properties for cyclic loading applications – relatively high toughness and strength. Their strength is mostly influenced by special properties of their carbide grains – the ability to deform plastically. The main influence on structure and properties of WC-Co hardmetal can be provided by changing its composition (cobalt and carbon) and adjusting the grain size (see Figure 10).

By the set of properties cermets (in most cases on bases of TiC or TiCN) can be located between hardmetals and tool steels [10–12].
In metalforming, primarily high alloyed tool steels or tungsten carbide-base hardmetals (with relatively high binder fraction) have been successfully used [2, 10, 13]. Cemented carbides (hardmetals) are used to perform coining (generally light coining of small pieces), wire-drawing, deep-drawing, blanking and bending dies in large industrial quantities. Steel bonded carbide composites are also occasionally used, particularly for deep-drawing tools [14–16].

The high elastic modulus of carbides, combined with their ability to incorporate fine details, makes carbide composites ideal tool materials for blanking punches and dies. As in many other metalforming applications, fine grain carbides are chosen for punches because of their edge retention capability and higher abrasion resistance [17].

Titanium carbide-based cermets are used in applications where in addition to high wear resistance, low specific weight, chemical inertness or high-temperature oxidation resistance is needed. Typically these cermets have a core-rim structure (see Figure 10), consisting of partially dissolved TiC particles, on which a binary carbide rim is grown through solution-reprecipitation process. The shape of TiC grains in the cermets is more rounded than in WC-based hardmetals (Figure 10).

Ceramic materials (e.g. ZrO_2, Si_3N_4) can also be used in principle to make punches for blanking. Their regrind life can be considerably longer that of hardmetals [18].

In the present research performance of TiC-based cermets as alternative to tool steels and WC-Co hardmetals in sheet metal blanking was studied.

1.3 Technology for increasing durability and reliability of tool steels and cermets

For better tool performance, material (steel, carbide composite) of the tool must be improved by changing its structure and properties. The two most relevant properties are toughness and hardness. Toughness prevents instantaneous fracture of the tool or tool edges [19], and hardness must be sufficiently high to avoid local plastic deformation so that tool geometry remains unchanged [20–21]. Toughness and hardness can be inter-dependent, and a good combination can be achieved by judicious heat treatment [22]. A combination of superior hardness (to maintain a high degree of dimensional accuracy) and good toughness (to avoid fracture failure) is a basic requirement both for tool steels and carbide composites.

It is known that the high-performance characteristics of submicron carbide composites (hardmetals) significantly exceed the performance of hardmetals with WC grains larger than 1 µm produced by conventional technology [23–29]. Well known is also high-performance of fine-grained PM tool steels.

In order to achieve an desirable properties of the tool steels various treatment technologies can be used. In cutting tool applications, PVD technology is widely used to coat HSS and hardmetal or cermet tools. In punching and forming tools application the use of PVD coatings gained much attention with the invention of CrN and TiCN coatings in addition to TiN and CVD treatment. The tribological situation in metalforming is typically characterized by high surface pressures, low deformation velocities, sometimes high temperatures and, depending on the lubrication, a variety of different friction conditions [4]. Composite treatment (duplex coatings) of highly loaded tools can give better performance than PVD coatings alone [30].

Compression sintering (HIP, Sinter/HIP) of cermets

Hot consolidation processes allow producing densities higher than achieved with conventional sintering and in some cases are designed to achieve full density. High density improves material properties and performance by reducing the porosity. Hot isostatic pressing (HIP) is probably the most extensively used process of hot consolidation of particulate materials.

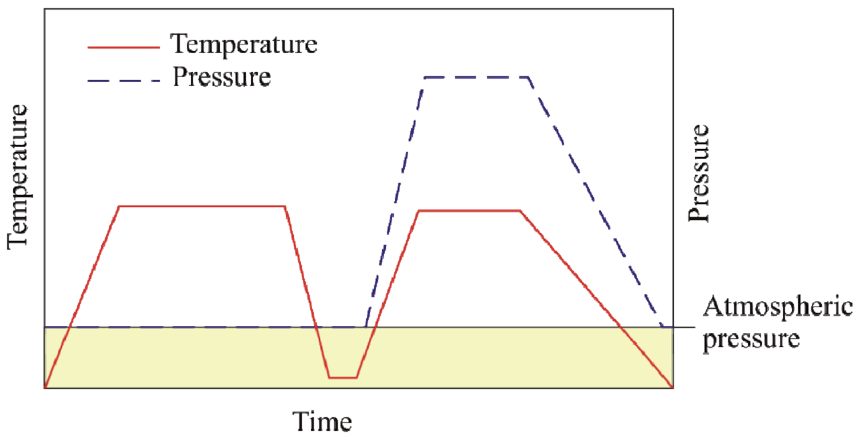

Figure 11 The scheme of Sinter+HIP cycle [9]

Sintering of cemented carbides (hardmetals) has historically been done in a vacuum or low pressure gas environment, but there has been an increasing emphasis on the either hot isostatic pressing (HIP) following vacuum sintering (sintering and HIP in different cycles, Sinter+HIP), or a single pressure sinter cycle (Sinter/HIP) to assist in the reduction of internal porosity [31]. The hot isostatic pressing of cemented carbides drastically improves transverse rupture strength without changing the wear resistance [9].

Sinter+HIP concept first need the powder material to be sintered by conventional method to a point, where all the pores are closed (residual porosity is below 8%), and then pressed. High pressures (usually 100 – 200 MPa) are used.
Figure 11 shows the schematic time-temperature-pressure profile of a typical Sinter+HIP cycle where the material is first sintered in a conventional sintering furnace, cooled and then introduced into HIP chamber and HIP'ed to full density. The major problem of the Sinter+HIP technique is the requirement of high temperatures for sintering which could also result in large grain growth.

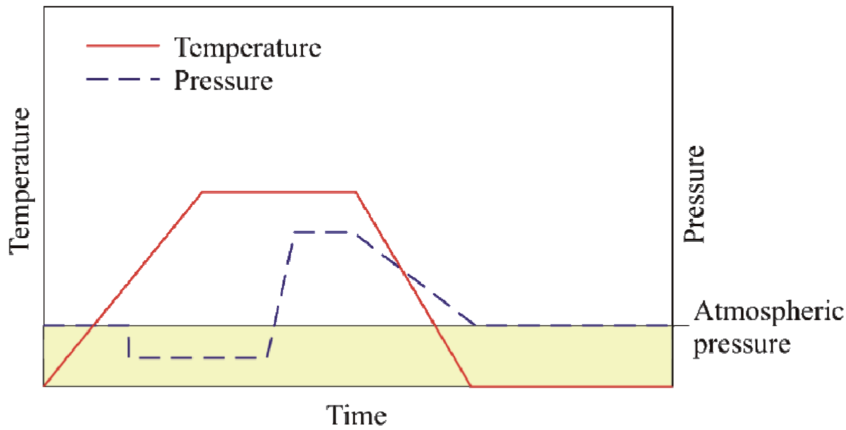

Figure 12 The scheme of Sinter/HIP cycle [9]

"Sinter+HIP in the Same Cycle" process allow performing the sintering and hot isostatic pressing in the same hot isostatic press and using only one single thermal cycle.

Another technique that has gained commercial significance is the process of Sinter/HIP. The main difference between this process and the "Sinter+HIP in the Same Cycle" technique is the use of substantially lower gas pressure employed with Sinter/HIP. The furnace used for Sinter/HIP is actually a vacuum furnace with special features, which allow small pressures (5 – 15 MPa) to be applied at elevated temperatures. Figure 12 shows the schematic time-temperature-pressure profile for a typical Sinter/HIP process. The application of Sinter/HIP allows reaching the density greater than 98.5% of theoretical and results in the uniform filling of pores [32].

A typical Sinter/HIP cycle that is used in the hardmetal industry is shown in Figure 13 [33], and it includes hydrogen dewaxing, vacuum sintering, followed by low-pressure assisted Sinter/HIP'ing.

Among strategies for decreasing porosity and improving the toughness of ceramic-metal composites (hardmetals, cermets) both Sinter +HIP (sintering and hot isostatic pressing in different cycles) and Sinter/HIP (pressure assisted sintering) are used. It has been shown for hardmetals [34–36 *etc*] that efficiency of sinter + HIP or sinter/HIP technology depends to a great extent on structural peculiarities. Sinter + HIP is more effective when the grain size is very fine and the cobalt content is low while sinter/HIP technique is better in the case of moderate grain size and cobalt levels.

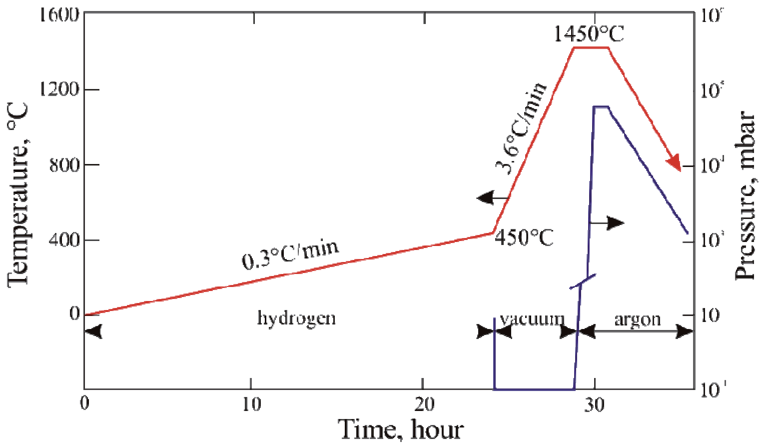

Figure 13 Typical industrial Sinter/HIP cycle for WC-Co composites

Research related to TiC and Ti(C,N) based cermets is more limited. It is possible to improve transverse rupture characteristics of Ti(C,N) cermets by utilizing sinter/HIP technology [37–38]**.** The improvements have been explained to be caused by the hindering nickel evaporation during sintering and lower porosity, affected by using argon atmosphere at the sintering temperature [38]**.** It has also been found that sinter/HIP atmosphere greatly influences the microstructure evolution of Ti(C,N) –based materials [37]**.** Effect of sinter/HIP technology on properties of TiC- NiMo cermets was carried out by authors of the paper [39]**.** It was concluded that similarly to WC-Co hardmetals utilisation of sinter/HIP enables to produce low-binder cermets of improved values of transverse rupture strength.

While efficiency of sinter/HIP technology for elimination of porosity and increase of strength (transverse rupture strength) has been proved both for WC-hardmetal and Ti(C,N) − or TiC-based cermets there has not been done any investigation focusing on two alternative technologies – sinter+ HIP (HIP after sintering in different cycles) and sinter/HIP of TiC-based or TiCN-based cermets.

Coating technology for tool steels

The properties and performance of cutting tools could be substantially improved by surface coating. Thin but hard coatings of single or multilayers of more stable and heat and wear resistant materials like TiC, TiCN, TiOCN, TiN, Al_2O_3 *etc* on the tough carbide substrate by processes like Chemical Vapour Deposition (CVD), Physical Vapour Deposition (PVD) etc at controlled pressure and temperature enhanced material removal ratio (MRR) and overall machining economy remarkably enabling reduction of cutting forces, increase in tool life, improvement in product quality etc. Use of thin coatings enables to reduce abrasion, adhesion and diffusion wear, reduce friction, enhance heat resistance and reduce thermal cracking. Application of coatings on tools and machine elements is, therefore, a very efficient way of improving their friction and wear resistance properties [40]. Today, 70% of the cemented carbide (hardmetal) tools used in the industry are coated.

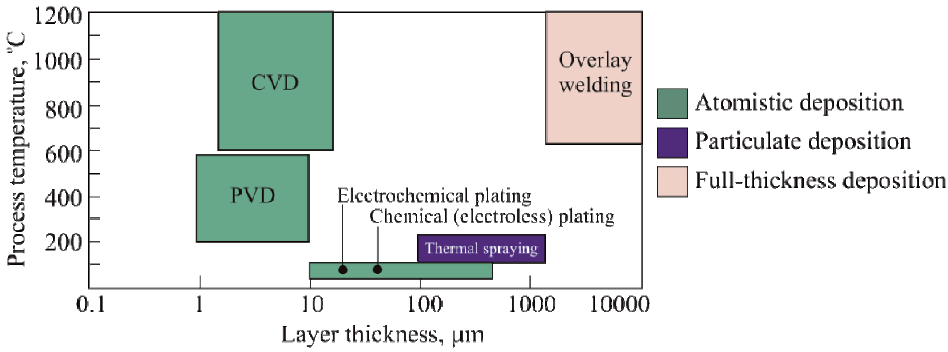

Figure 14 Typical value of coating thickness and process temperature of today's tribological coating methods [40]

Surface coatings of tribological applications are associated with deposition temperatures ranging from room temperature to over 1000 °C as shown as an example in Figure 14. The coating thickness ranges from fraction of microns to several millimeters. Typically, the atomistic methods produce the thinnest coatings. Some methods involve high deposition temperatures that may give undesirable phase transformations, softening or shape changes of the coated component [41–42].

The reason PVD is becoming increasingly favorable over CVD is the fact that the coating process occurs under much lower temperature (Figure 14). The high temperature during the CVD process causes deformation and softening of many cutting tool substrates and particularly high-speed steels. Another advantage of applying the PVD technique is the ability to deposit much thinner coatings. And so, it is much more promising for the deposition of multi-layered coatings, which have been found to reduce wear considerably.

PVD process coatings and nitride work well with high-speed and high-alloy tool steels such as M2, M4, CPM-10V, S390 and S690. PVD process temperatures fall more than 30 °C below the tempering temperature for high-speed and high-alloy tool steels, nearly eliminating distortion and part growth. Due to high processing temperature of CVD coatings and thermal diffusion, post-heat treat is commonly required to achieve acceptable substrate material hardness.

CVD coated hardmetals have been a huge success since their introduction in late 1960's [43]. Since then, chemical vapor deposition technologies have advanced from single layer to multi-layer versions combining TiN, TiCN, TiC and Al_2O_3 [44–45]. Modern CVD coatings combine high temperature and medium temperature processes in complex cycles that produce excellent wear resistant coatings with a total thickness of 4–20 µm [46].

However, the high deposition temperature (950–1050 °C) during CVD results in diffusion of chemical elements from the hardmetal substrate to the coating during growth. The main effect is an embrittlement of the coating edge [47]. In addition, the chemistry of the CVD process results in more rapid growth at the cutting edge resulting in an even coating thickness. Therefore, there was a string driving force to find coatings that could be deposited at lower temperatures in order to allow tools with sharper edges to be coated without any embrittlement effect. The solution was PVD where deposition temperature can be kept at around 500 °C.

PVD coatings, with deposition temperature of 400–600 °C, are gaining greater acceptance in the market place. Over the last decade, they have been successfully applied to hardmetal and cermet cutting inserts. They offer performance advantage in applications involving interrupted cuts, those requiring sharp edges, as well as finishing and other applications [48–50]. The metal cutting performance of PVD coated tools depend strongly on the composition, microstructure, internal stresses and adhesion of the coating to the substrate as well as the substrate composition and geometry [51].

An important factor is the preparation of substrate surface before deposition – geometry and hardness. In paper [52] there were compared blanking punches with coatings deposited on the surfaces with different levels of preparation and it seemed, that surface with lower roughness exhibits intensive wear compared surface with higher roughness.

Recent studies show that hardness and modulus of elasticity and with them the ratio H/E of the hard coatings can be controlled by its chemical composition and by deposition parameters used for the formation of the coatings (see Figure 15) [54–55].

Coating thickness is a critical factor that affects the hard coating wear rates. It has been shown [53] that mechanical properties and the hardness of thin (Ti,Al)N coatings with thickness in range of 3 – 8 µm for cemented carbides as substrates significantly affect the wear rates. According to the coating growth mechanism the thicker is coating the greater is superficial grain size that leads to hardness and wear resistance reduction [53].

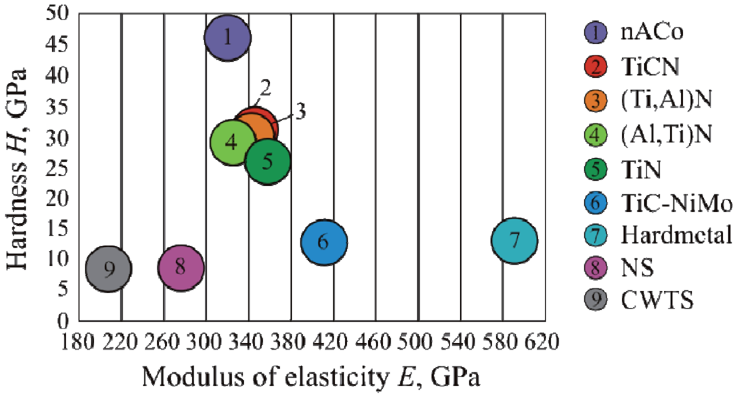

Figure 15 Hardness - modulus of elasticity map of some PVD coatings and substrates [53]

The coating adhesion proved to have an effect on coating wear rate and lifetime [56].

Surface roughness of the coating proved to be an important factor in sliding wear and fatigue under cyclic indentation process [57–58]. Generally, the smoother surface proves the lower wear rates [59].

The sharpness of the edge of the punch is crucial for blanking process. Coatings are at a disadvantage in this respect because they reduce the sharpness of the cutting edge. This may limit the applicability of coatings for certain working operations. In any case, it limits the thickness of the coating that can be applied [59].

PVD process chain includes pre-PVD processes and post-PVD processes. Pretreatment processes such as plasma etching and chemical etching influence adhesion, grain growth, stress at substrate surface and coating structure, whereas post-PVD process influence smoothness of coating surface.

PVD coatings attribute excellent cutting performance to cemented carbide (hardmetal) inserts [60]. The reason that PVD has more and more taken over with regards to deposition of many coatings is the advantages that lower coating temperatures give with regard to micro-toughness. In addition, the coatings are crack free as opposed to CVD coatings and have a residual stress that is beneficial in some applications [47]. Previous studies have shown that cemented carbide cutting tools coated by PVD technology offer proven performance over their CVD coated counterparts [61].
PVD TiCN, TiAlN, AlCrN deposited as a mono-layer hold a dominant position in the field of hard coatings to improve the wear resistance of blanking tools [1].

In the present research devoted to investigation of performance of tool materials in blanking, thin PVD coatings were utilized for strengthening of HSS. Coatings were not applied on carbide composite (cermet, hardmetal) tools.

Heat treatment

Tool steels are machined in the soft-annealed state and then hardened and tempered. The microstructure in the soft-annealed state consist of a basic ferritic matrix and carbides. When a tool steel is hardened the carbides in the basic matrix are thoroughly dissolved so that the alloy content of the matrix is increased until the hardening process can be initiated.

Response to tempering can be divided into a number of classes. According to [62] highly alloyed high-speed steels are examples of class of tool steels that undergo secondary hardening associated with precipitation of alloy carbides in the tempered martensite matrix.

According to phase diagram, WC-Co hardmetals are heat-treatable, but in practice hardening is not used for hardmetals. From the other side, major stage of production of cermets with steel binder, where it gets its final material structure and demanded properties, is the heat treatment.

Steel-bonded titanium carbides (with TiC content up to 50 wt%) respond to heat treatment and are machinable by conventional means when the binder is in the annealed condition. Fully hardened steel-bonded carbides can be tempered at varying temperatures, thereby obtaining greater toughness than WC-Co. However, this gain in toughness is accompanied by some sacrifice in hardness. After quenching and tempering cermets with steel binder have great hardness and wear resistance.

TiC-based cermets with Ni-steel binder (Ni>14 wt%) investigated in present research after sintering have a microstructure of stable austenite occasionally including traces of bainite. Such carbide composites heat treatment provide no noticeable improvement in the strength or in the hardness [16, 63, 64].

1.4 Objectives of the study

Sheet metal blanking (stamping) tools work in complex conditions – severe wear accompanied by high contact and bending stresses and mechanical loads of cyclic nature. As stated previously, material loss during sheet metal working takes place mostly due to abrasive and / or adhesive wear. The two relevant properties of wear resistant tool material used in material selection, as well as development of new materials and related technologies are hardness and toughness. Toughness prevents instantaneous fracture of the tool and hardness must be sufficiently high for decreasing wear and avoiding plastic deformation so that tool geometry remains unchanged. For better metalforming tool life high-alloy tool steels and ceramic-metal composites (hardmetals, cermets) can be utilized. Additional increase in durability of tool can be achieved utilizing thin coatings, particularly PVD coatings.

Motivation of the current applied research was to increase the performance characteristics, particularly durability of sheet metal blanking tools utilizing advanced TiC-based cermets and high-performance tool steels strengthened by thin PVD coatings.

The research focused on the following topics:

1. Study of the performance of carbide composites particularly TiC-based carbide composites in sheet metal blanking;
2. Investigation of the effect of advanced sintering technologies (HIP, Sinter/HIP) on performance of TiC-based cermets as alternative to WC-Co hardmetal tool materials;
3. Study of the performance of high-alloy steels strengthened by PVD coatings in sheet metal blanking;
4. Revealing possibilities of utilizing simple simulating wear tests for assessment of blanking tool performance.

2 MATERIALS AND EXPERIMENTAL

2.1 Materials

Performance of blanking tools can be enhanced utilizing hardmetals and cermets or high-performance tool steels, particularly strengthened by PVD coatings.

Work material used in functional (blanking) tests, tool materials (ceramic-metal composites and tool steels) and PVD coatings utilized are characterized in present section of the work.

2.1.1 Ceramic-metal composites

The study covers mainly TiC-based cermets (grades with TiC content 70 and 75 wt%) prospective as tool materials in blanking of sheet metal. As reference material the WC-based hardmetal (grade C13, 85 wt% WC) widely used in metalforming was also under investigation. All composites were produced in the laboratory of Powder Metallurgy of TUT. Composition, the main structural characteristics and mechanical properties of cermets are presented in Table 2.

Table 2 Structural characteristics and mechanical properties of cermets

Grade	Carbide		Binder		HV**	R_{TZ}**, GPa	E, GPa	$R_{C0.1}$**, GPa
	Composition, wt%	Grain size d, µm	Composition, wt%	Microstructure				
T70/14	TiC, 70	2.1	Fe-14Ni, 30	austenite*	1250-1280	2.1-2.3	400	2.3-2.6
T75/14	TiC, 75	2.0	Fe-14Ni, 25	austenite*	1360-1390	1.8-2.0	410	2.8-3.0
T75/14 -H	TiC, 75	2.0	Fe-14Ni, 25	austenite*	1360-1390	2.3-2.5	410	2.8-3.0
C13	WC, 85	1.8	Co, 15	Co(W)	1300-1320	2.7-2.9	590	2.8-3.1

* Traces of martensite
** Properties of different batches

Figure 16 shows the microstructures of the carbide composites with carbide fraction of ~80 vol%. The microstructure of WC-composite (grade C13) consist of WC-grains mainly of angular shape embedded in the binder phase (see Figure 16 A). The shape of TiC grains is more rounded (see Figure 16 B).

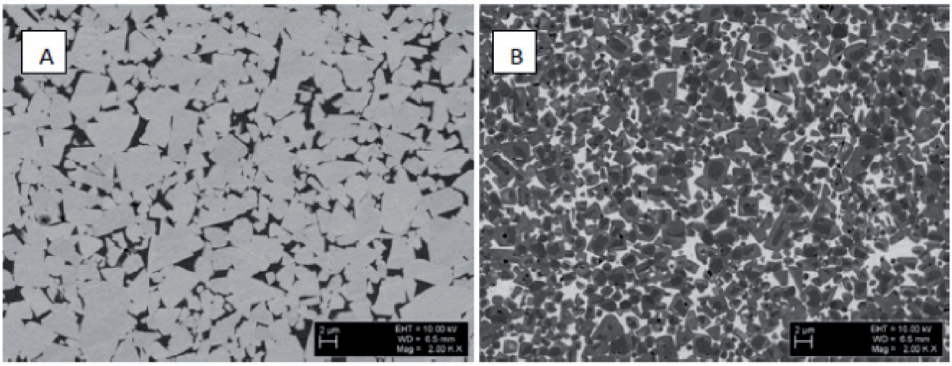

Figure 16 SEM images of investigated carbide composites
A – WC-based hardmetal (C13), B – TiC-based cermet (T75/14)

2.1.2 Tool steels for metalforming applications

As a tool materials for investigation, high-performance steels S390, S690 and Vanadis 4E were chosen. Chemical composition and mechanical properties of tool steel grades are presented in Table 3.

Table 3 Chemical composition and mechanical properties of the tool steels for plastic working applications (S390 MicroClean, S690 MicroClean and Vanadis 4 Extra SuperClean steels by Böhler) [65]

Grade	Chemical composition, wt%						Mechanical properies		
	C	Cr	Mo	V	W	Co	HRC	HRA	R_{TZ}, MPa
S390	1.6	4.8	2.0	5.0	10.5	8.0	65	84	4500
S690	1.33	4.3	4.6	4.1	5.9	-	65	84	4000
Vanadis 4E	1.4	4.7	3.5	4.0	-	-	60	82	4300

Heat treatment data of tool steels under investigation are presented in Table 4.

Table 4 Heat-treatment data of selected Böhler (Uddeholm) HSS

Steel grade	Hardness after annealing	Hardening temperature °C	Quenchant °C	Obtainable hardness HRC
Böhler S390	max. 300 HB	1150-1230°C	Oil, Vacuum, Salt bath (500-550°C)	65-69
Böhler S690	max. 280 HB	1150-1200°C		64-66
Uddeholm Vanadis 4E	~230 HB	940-1150°C		60

The wear properties of high speed steel result from a combination of hard matrix and a distribution of hard carbides generated through an appropriate starting chemistry and heat treatment program (see Table 4) [62].

2.1.3 Coatings and their properties

The PVD coatings studied in the present work were deposited in the Laboratory of PVD coatings at TUT. Platit π-80 arc-ion plating PVD unit was used for deposition of hard coatings. Unit has two rotating cathodes embedded into the door (Platit patented LARC® - Lateral Arc Rotating Cathodes technology) of the vacuum chamber. Coatings were deposited using two cathodes – Ti and Al.

Table 5 Process parameters for coating deposition [66]

Coating	Bias voltage, V	Pressure, mbar	Cathode arc current, A	Temp., °C	Ar/N_2; C_2H_2 flow, cm^3
TiN	-70 – -120	8×10^{-3}	(100-125)	450	6/200
(Ti,Al)N	-60 – -150	8×10^{-3} – 1.5×10^{-2}	(85-125) / (65-115)	475	6/200
TiCN	-60 – -120	$(5\text{-}7)\times10^{-3}$	120-130	450	6/165-180; 7-39

Coating thickness was set to 3.4 μm. Standard Platit coating recipes were used in order to deposit the coatings. Table 5 shows the main process parameters for deposited coatings.

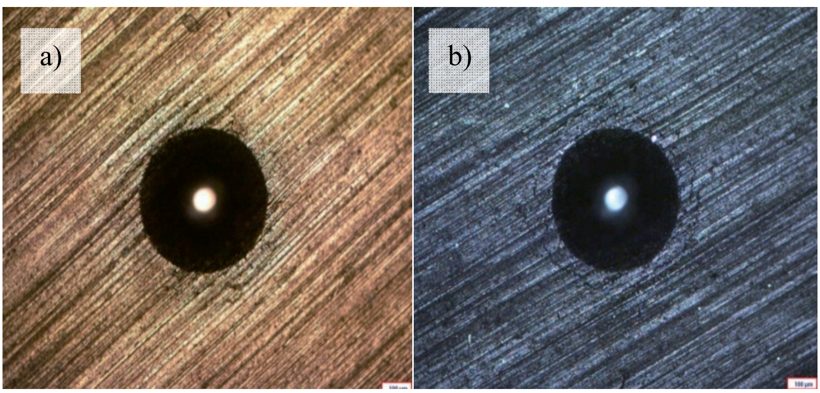

Figure 17 Rockwell HRC indentation cavity of TiN and (Ti,Al)N coating on steel S390 substrate: a) TiN; b) (Ti,Al)N

Adhesion of TiN and (Ti,Al)N coatings to the surface of the punches and dies produced from the Böhler S390 Microclean steel substrate was studied using Rockwell adhesion test method [67].

In order to test the adhesion quality of the coatings, the well-known Rockwell adhesion test method was used [67]. A Rockwell hardness tester, conforming to the requirements of EN ISO 6508-2 and VDI 3198 (1992) standard, was applied. Every sample was indented at three different representative locations as minimum. Indentations were made in a direction perpendicular to the specimen surface. Sample surfaces were free from dust, oil and other contaminations. Tests were performed on Zwick/ZHR8150 hardness tester. A load of 1495 N (150 kgf) of Rockwell A scale, was used in order to conform the relevant standards [67]. A conical diamond indenter with a 120° tip angle penetrates into the surface of a coated specimen inducing severe plastic deformation to the substrate and fracture (cracking, chipping, debonding) of the coating. The indented samples were then analysed with an optical microscope at a magnification of 100× and 500×. Result were classified into the categories given in the CEN/TS 1071-8 standards [67].

The results of Rockwell adhesion tests revealed a common trend between all coatings. Coating adhesion was found to be sufficient for both types of coatings (Class I – cracking adhesive delamination of the coating). Figure 17 show the indentation trace of Rockwell cone into S390 steel coated by TiN and (Ti,Al)N with magnification of 100×. No delamination is observed in any of the coating types. Small radial cracks are visible on indentation trace diameter of TiN coating and a more pronounced circular crack pattern was obtained for (Ti,Al)N coating.

2.2 Wear and mechanical properties testing procedure

The prediction and control of wear is one of the most essential problems emerging in the design of sheet metal cutting operations.

2.2.1 Wear

Adhesive wear tests were performed by a cutting method (close to ISO 3685-1999) by turning mild steel (HV≤160) at low speed (v<12 m/min), simulating blanking tools wear in the prevalence of adhesion [64]. The wear resistance was determined as the length of cutting path L_1, when the height h of the wear land at the specimen (tool) nose achieved 0.3 mm (Figure 18). The critical height h=1 mm of wear land corresponds to wear rate of working tool parts (punch and die), when they should be sharpened. The wear resistance confidence interval did not exceed 10% when the number of test pieces was at least three. An excellent correlation between the wear resistance of WC-Co hardmetals determined by this method and blanking die wear was reported in previous works [68, 69].

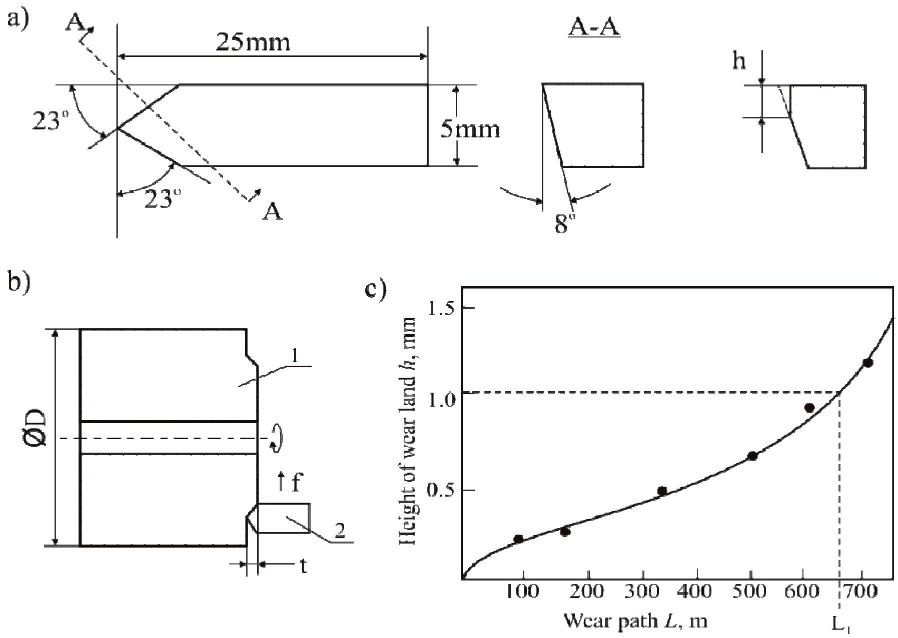

Figure 18 The scheme of simulative adhesive wear testing: a) tool, b) scheme of testing, c) kinetics of wear
1 – mild steel to be turned; 2 – specimen; h – height of wear land; L_1 – adhesive wear resistance; L – wear path

Sliding wear tests were performed in accordance with ASTM standard B611-85 procedure, without abrasive at loading F=40 N and wear length L=4000 m. The volumetric wear rate was calculated as $\Delta V=\Delta m/\rho$, where Δm – the average (of three specimens) mass loss and ρ - the density of the material.

Abrasive wear tests were performed using rubber-rimmed rotary machine (modified ASTM G65-94 method) as follows: abrasive – quarts sand (3kg, particle size 0.1–0.2 mm), velocity of wheel 0.24 m/s, testing time 10 min and load 3N. The wear was estimated as volume loss in mm^3.

2.2.2 Mechanical properties

Transverse rupture strength R_{TZ} was determined in accordance with the ISO 3327 method (using specimen B) [70] and Vickers hardness in compliance with EN-ISO 6507 [71]. The specimens with dimensions 5x5x17 mm were ground to a surface finish about R_a=2.5 µm on four sides. Twenty specimens (per cermet or steel) were tested and statistically treated to obtain statistically reliable Weibull distribution curves (failure probability curves) to ensure confidence interval of < 4% with probability factor 98%.

Fatigue tests resembled those of three point bending fatigue – fatigue of specimen 5x5x17 mm under sinusoidally alteracting transverse bending load at the stress ratio R=0.1 and frequency f=30 Hz, up to 10^7 loading cycles. The resistance to fatigue damage was characterized by the factor of fatigue sensitivity – intensity in the decease of strength with an increase in the loading cycles from $N_3=10^3$ to $N_7=10^7$ as ΔS_{3-7}.
Surface fatigue test data are in correlation with three point bending fatigue data according to [72].

2.3 Functional testing in blanking of sheet steel

2.3.1 Test method of durability in blanking

The procedure of the durability functional test – wear tests in blanking – resembled that in service, i.e. blanking of grooves into low carbon electrical sheet steel (with hardness of 140 HV and a thickness of 0.5 mm) using a three-row die reinforced with cermets or steels under investigation. Dies were mounted on an automatic mechanical press (see Figure 19).

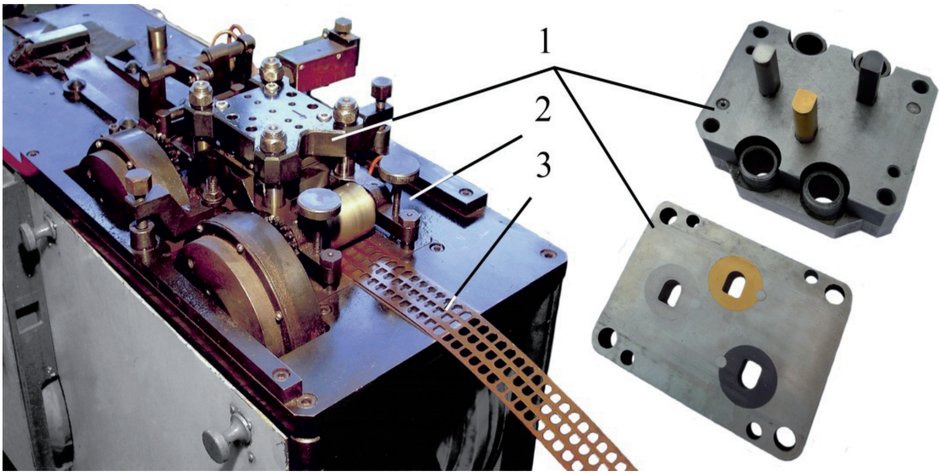

Figure 19 Functional testing of durability in blanking: 1– three-row die, 2 – mechanical press, 3 – sheet steel band

The wear resistance was evaluated by the measurement of the side wear of the die (increase in diameter ΔD) after an intermediate service time $N=0.5\times10^6$ strokes (cermets, hardmetal) and $N=0.4\times10^6$ (tool steels), as N/ΔD (lifetime in stokes per 1mm of the side wear) [73, 74]. The side wear was measured using the coordinate measuring machine Mitutoyo STRATO 9-166 in fixed environmental conditions (constant room temperature 20±2 °C and humidity of 40%) as an average of 4–6 measurements to ensure confidence interval of 10% with the probability of 95%.

2.3.2 Work material

The general category of magnetically soft materials encompasses many types of materials, including iron-nickel, iron-cobalt and iron-aluminum, ferrites and austenitic stainless steels. The most commonly used magnetically soft materials: low-carbon electrical steels and non-oriented electrical silicon steels. Low-carbon steels are used for many applications that require less than superior magnetic properties. The combination of magnetic properties, coupled with low price and excellent formability, makes low-carbon steel especially suitable for applications such as fractional-horsepower motors which are used intermittently.

Electrical sheet that is to be blanked usually ranges in thickness from 0.343 to 0.607 mm. Thinner or thicker stock is used for special applications.

M700 electrical steel of 0.5 mm thickness and 53.1 mm in width has been selected as work material in the current study. M700-50A is a cold-rolled non-grain oriented electrical sheet steel. Chemical composition and mechanical properties of work steel are given in Tables 6 and 7. The structure of tested electrical steel is presented on Figure 20.

Table 6 Chemical composition of electrical steel M700-50A (1.0815)

Composition, wt%					
C	Al	Mn	P	S	Si
0.05	0.75	0.75	0.25	0.05	2

Table 7 Mechanical propertiesof steel M700-50A

HV	R_m, MPa	$R_{p0.2}$, MPa	A, %
140	372	240	23

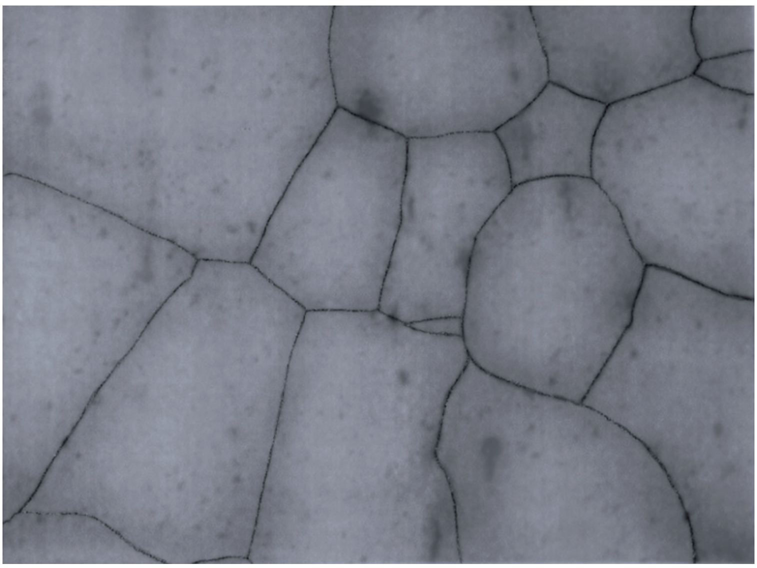

Figure 20 Structure of tested electrical steel M700 (magnification 500×)

2.4 Microstructural studies

Microstructural examinations were complemented by SEM and XRD investigations performed on the scanning electron microscope JEOL JSM 840A and diffractometer Bruker D5005, respectively.

3 EFFECT OF COMPOSITION AND TECHNOLOGY ON DURABILITY AND RELIABILITY OF BLANKING TOOL MATERIALS

3.1 Advanced technology for enhancing of TiC–carbide based cermets

The properties of hardmetals and cermets can be influenced through adjusting production parameters, such as sintering temperature and isostatic gas pressure. The grain size of carbide, porosity and contiguity highly influence properties of ceramic-metal composites.

Among strategies for decreasing porosity and improving the toughness of ceramic-metal composites (cermets, hardmetals) Sinter+HIP (sintering and hot isostatic pressing in different cycles) and Sinter/HIP (gas pressure assisted sintering) are used. Utilization of both technologies should help effectively in eliminating the last trace of porosity in composites.

3.1.1 Sinter/HIP

The properties of cermets are greatly influenced by parameters of Sinter/HIP. The effect of sintering temperature on mechanical and wear resistance properties of alloy T75/14-H is presented in Figure 21. The dependence of properties on isostatic gas pressure is shown in Figure 22.

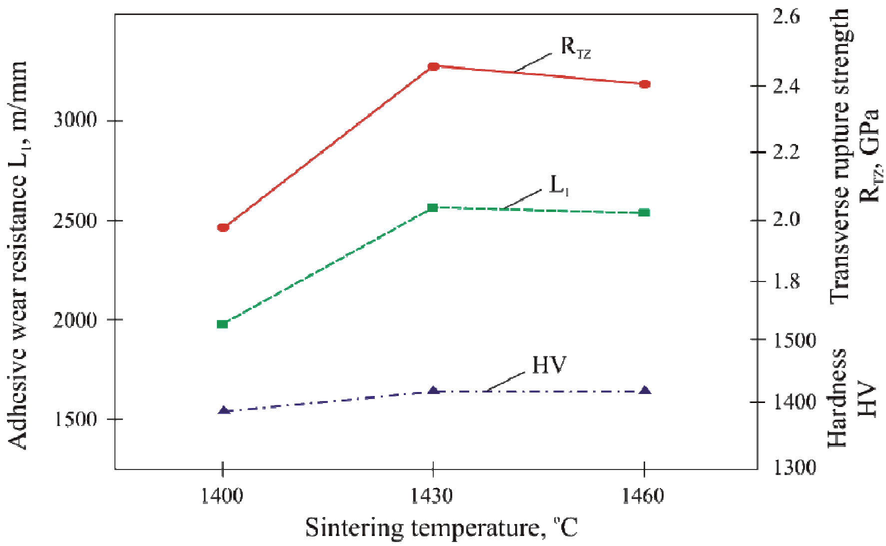

Figure 21 Influence of sintering temperature on properties of the cermet TiC75/14-H (compression sintering at p = 60 Bar)

Gas compression during sintering (Sinter/HIP) has a positive effect on the performance (transverse rupture strength, adhesive wear resistance) of cermet. Hardness exhibits a low sensitivity to sintering parameters. These results coincide with other authors' investigating effect of Sinter/HIP on performance characteristics of hadmetals [34–36 *etc*] and cermets [37–39].The maximum values of the properties (strength, wear resistance) can be observed at sintering temperature 1430 °C and pressure 60 Bar.

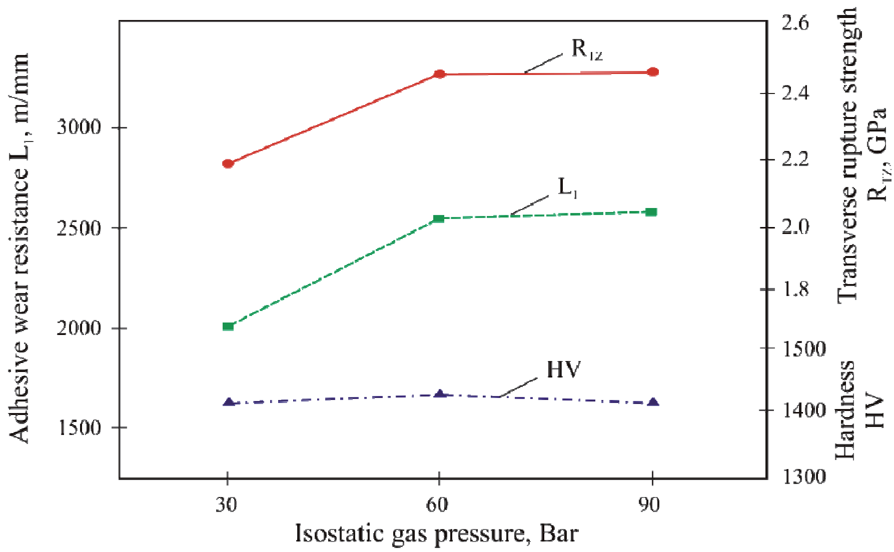

Figure 22 Influence of isostatic gas pressure on the properties of the cermet TiC75/14-H (sintering temperature 1430 ℃, time 60 minutes)

The Weibull-plots (failure probability curves) of transverse rupture strength of alloy T75/14 sintered by ordinary vacuum sintering and using Sinter/HIP technique are presented in Figure 23.

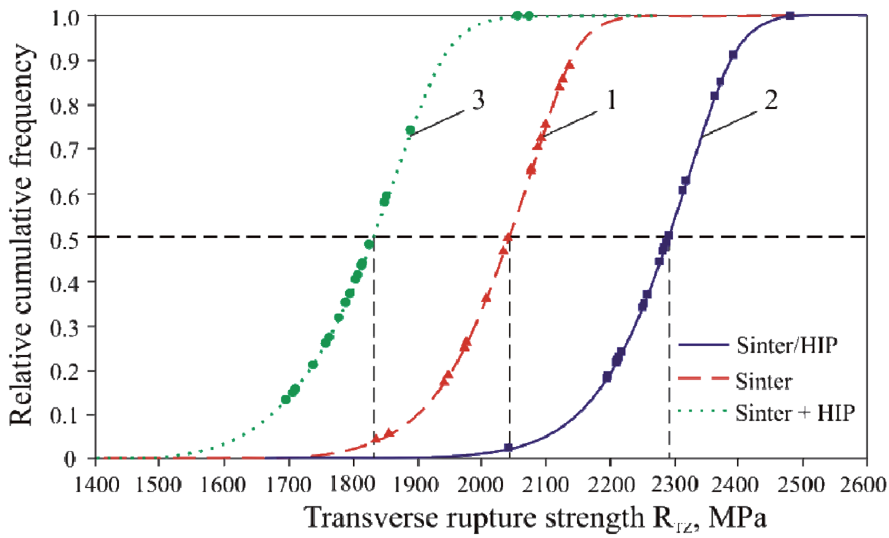

Figure 23 Strength R_{TZ} in Weibull-plots: 1 – vacuum sintering (1430 ℃), 2 – Sinter/HIP (1430 ℃, 60 Bar), 3 – Sinter+HIP (1500 Bar, 1370 ℃)

The results of SEM-studies presented in Figure 24 refer to influence of different sintering techniques on the microstructure of alloys. The microstructure of alloys sintered at optimal parameters (sinterhipped at 1430 °C) ensuring maximized performance is featured by microstructure of higher homogeneity (uniform distribution of phases) and lower porosity.

The received results refer to an obvious superiority of Sinter/HIP technology. However, increase of strength of sinterhipped composite is not accompanied by a marked decrease in the scatter of strength data.

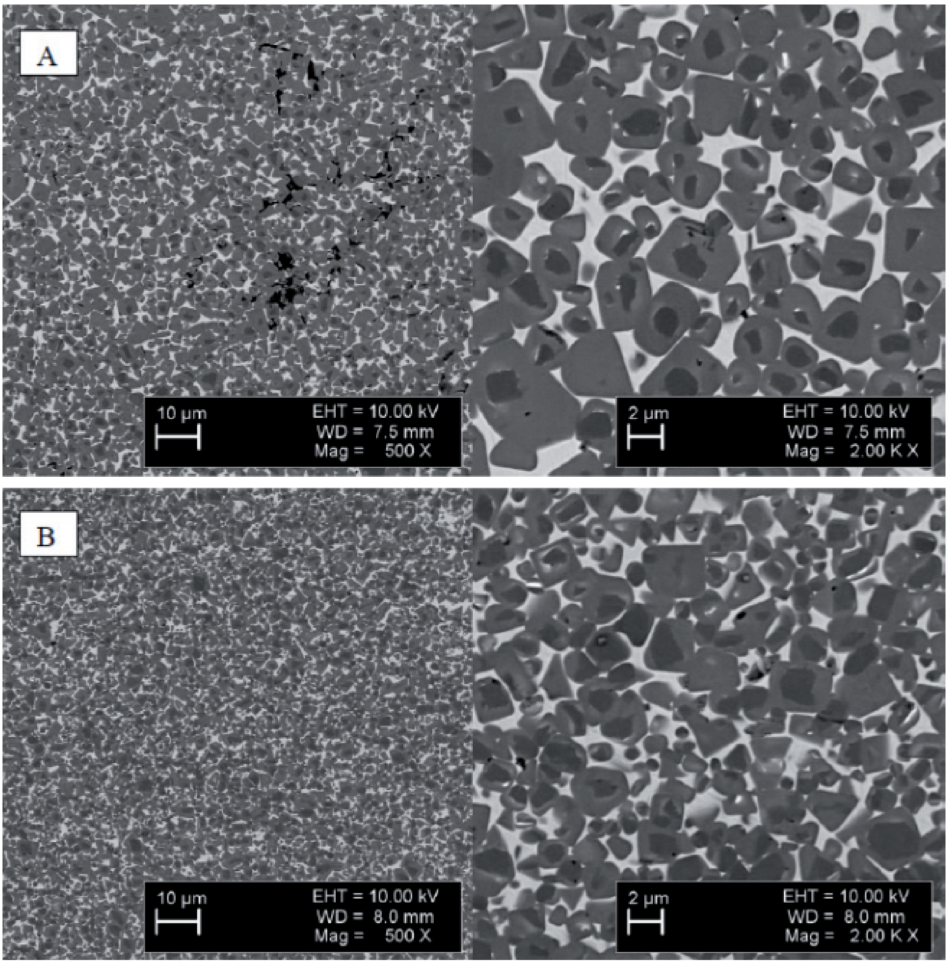

Figure 24 Microstructure of cermet TiC75/14 sintered by different techniques: A – ordinary vacuum sintering technology, B – optimal (Sinter/HIP) technology.

3.1.2 Sinter+HIP in different cycles

Pressurized sintering carried out in two different cycles (Sinter+HIP or Sinter + Sinter/HIP) is less effective than one-cycle Sinter/HIP process.

Similar results were obtained by other researchers of WC-Co hardmetals [34, 36, 75].

Performance characteristics of cermet T75/14 sintered by different modes (vacuum sintering, Sinter/HIP, sintering + Sinter/HIP in different cycles) are demonstrated on Figure 25.

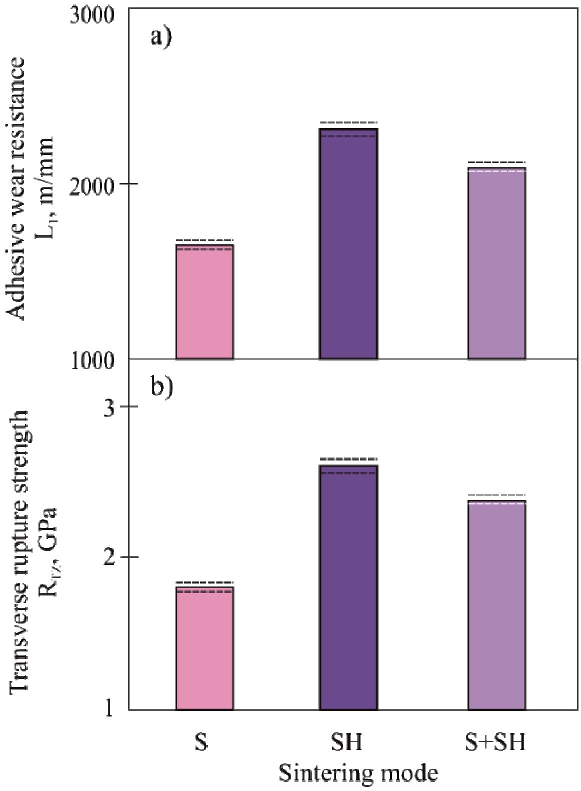

Figure 25 Adhesive wear resistance (a) and transverse rupture strength (b) of cermet T75/14 sintered by different modes (S - ordinary vacuum sintering, SH - Sinter/HIP, S+H - sintering + Sinter/HIP)

Figure 26 demonstrate the dependence of transverse rupture strength of cermet T75/14 on HIP process temperature (gas compression during HIP – 1500 Bar, 60minutes). It can be seen that increase in HIP temperature above eutectic temperature in the system TiC-Fe (~1350 °C) causes decrease in the transverse rupture strength. In other words, increase of temperature T≥1340 °C results in the strength decrease of hot isostatically pressed alloy's in relation to vacuum sintered one [16].

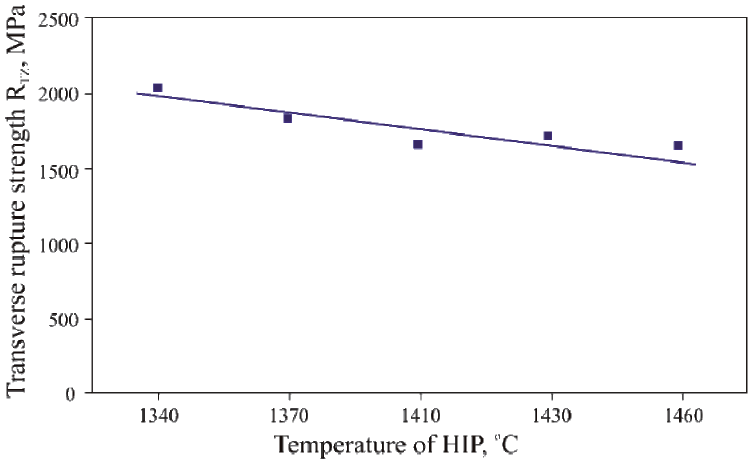

Figure 26 Influence of temperature of HIP on strength of TiC-based cermet T75/14 (vacuum sintered at 1430 °C)

3.2. Durability of blanking tools

Hardmetals and cermets as well as tool steels strengthened by thin coatings are mainly used in service conditions where high wear resistance either in abrasive conditions or at elevated temperatures (high speed cutting) is required. Carbide composites, particularly cermets, are not so often used in non-cutting (metalforming) operations owing to complicated service conditions where severe wear (particularly adhesive wear) is accompanied by high mechanical loads of cyclic and dynamic nature. In such conditions primarily high alloyed, particularly PM steels or WC-Co hardmetals with increased binder content have been successfully used.

3.2.1 Performance of cermets

Results of functional wear test (conducted as the blanking of grooves into the electrotechnical sheet steel) are shown in Figures 27 and 28 as wear contours ΔD - H (side wear ΔD depending on the depth H from the cutting edge of the die and punch).

Table 8 Composition of a 3-position (3-row) die

Position of die	1	2	3
Grade of cermet	T75/14	T75/14-H	C13

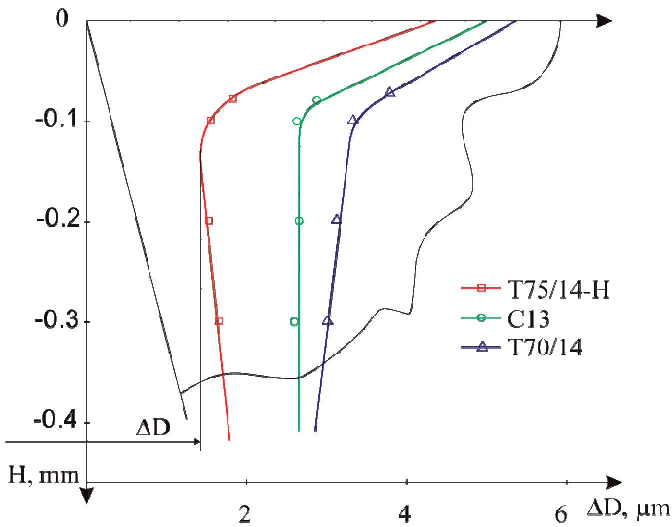

Figure 27 Wear contours of dies made of cermets

During testing (N=0.5×10^6 strokes) of the die (three row die reinforced with the samples of cermets/hardmetals (Table 8)) neither fracture nor brittle macrochipping of cutting edges was detected. Cutting edges became blunt as a result of uniform wear.

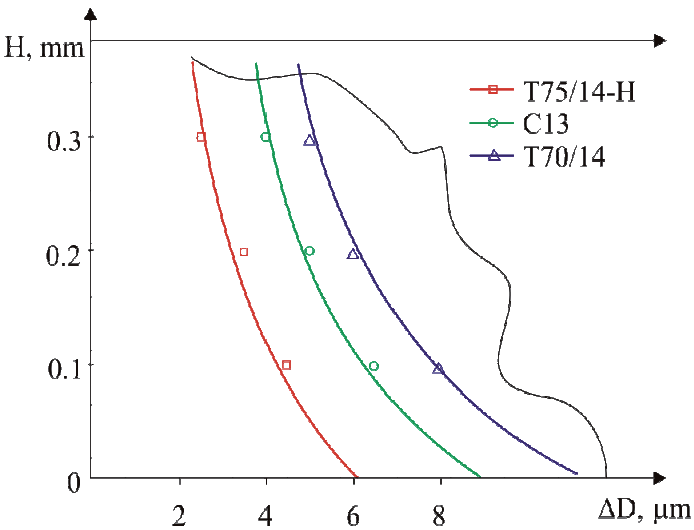

Figure 28 Wear contours of punches made of cermets

The wear contours of die (Figure 27) and punch (Figure 28) demonstrate the superiority of the advanced TiC-cermet (grade T75/14-H) produced by Sinter/HIP technology over hardmetal C13 and cermet T70/14. The advanced

TiC-cermet demonstrated blanking performance exceeding that of ordinary composites by factor of 1.5 – 2.

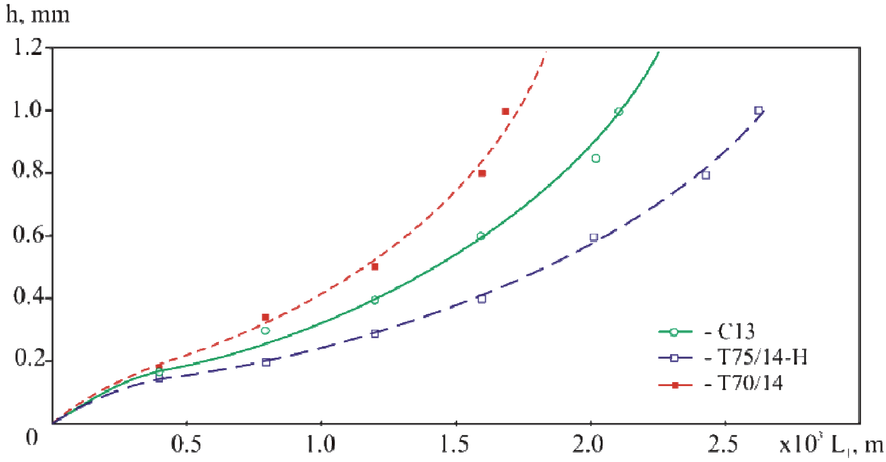

Figure 29 Adhesive wear curves of the cermets

The results of the adhesive wear test (as wear kinetic curves h-L, Figure 29) confirm the results of blanking trials – superiority of the advanced TiC-based cermet. These results refer to the existence of correlation between composite's blanking performance and its adhesive wear resistance (Figure 30). There is no such correlation between blanking performance and abrasive or sliding wear (see Figure 30).

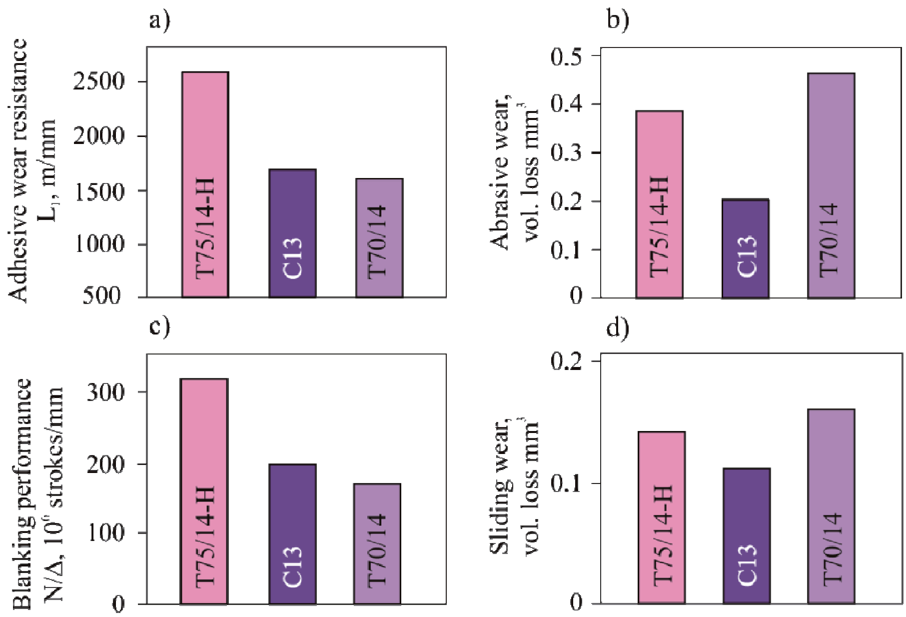

Figure 30 Adhesive resistance (a), abrasive wear (b), blanking performance N/ΔD (c) and sliding wear (d) of cermets

As reported in [68] the removal of material during wear has a selective nature and starts preferably in the binder by micro-cutting (abrasion) or extraction (adhesive wear) [74, 76]. Figure 31 compares wear of the surfaces after blanking and testing of adhesive wear. Surface failure mechanism occurring during adhesive wear and sheet metal blanking seemed to be similar – the distinctive nature of the worn surfaces confirms that binder extraction prevails in both cases (see Figure 31).

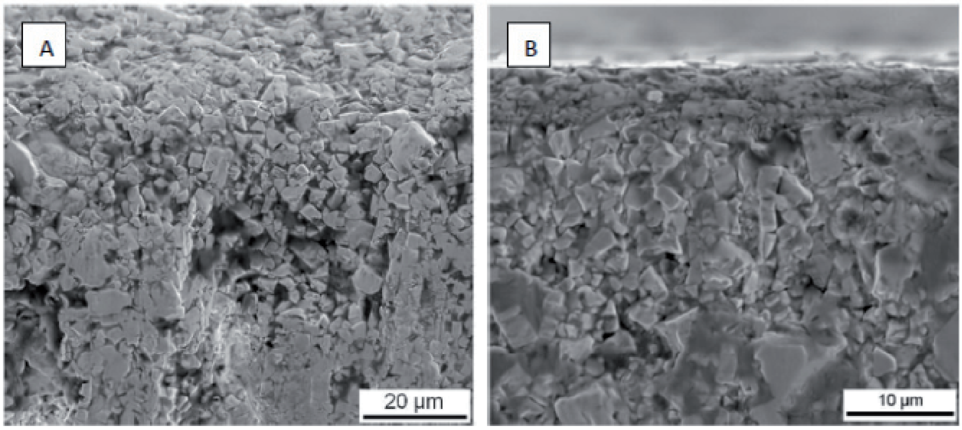

Figure 31 SEM images of cermets surface after blanking (A) and testing of adhesive wear (B)

After removal of binder, the carbide lose their steady protective envelope (generating favourable compressive stresses), resulting in a drop of their resistance to brittle failure [73]. Thus, the increase in the composite's resistance to adhesive wear (removal of binder) results in the increase of its resistance to brittle failure (microchipping, cracking).
Blanking performance, as revealed in present research, can be related besides adhesive wear resistance also to fatigue sensitivity. Figure 32 shows the results of fatigue trials – the Wöhler plots of the advanced TiC-based cermet T75/14-H and WC-based hardmetals C13. Although the transverse rupture strength (R_{TZ}=S_1=2.9 GPa) and cyclic strength at low cycles ($N<10^3$) of the WC-Co hardmetal exceed those of the TiC-based cermet (R_{TZ}=2.4 GPa), the fatigue limits at $N>10^5$ show opposite result – the superiority of the cermet over hardmetal (S_7=1.7 GPa against 1.5 GPa). It means that the fatigue sensitivity i.e. the intensity in the decrease of strength with the increase in loading cycles (the slope S –N of the Wöhler plot) of TiC-based cermet, is lower.

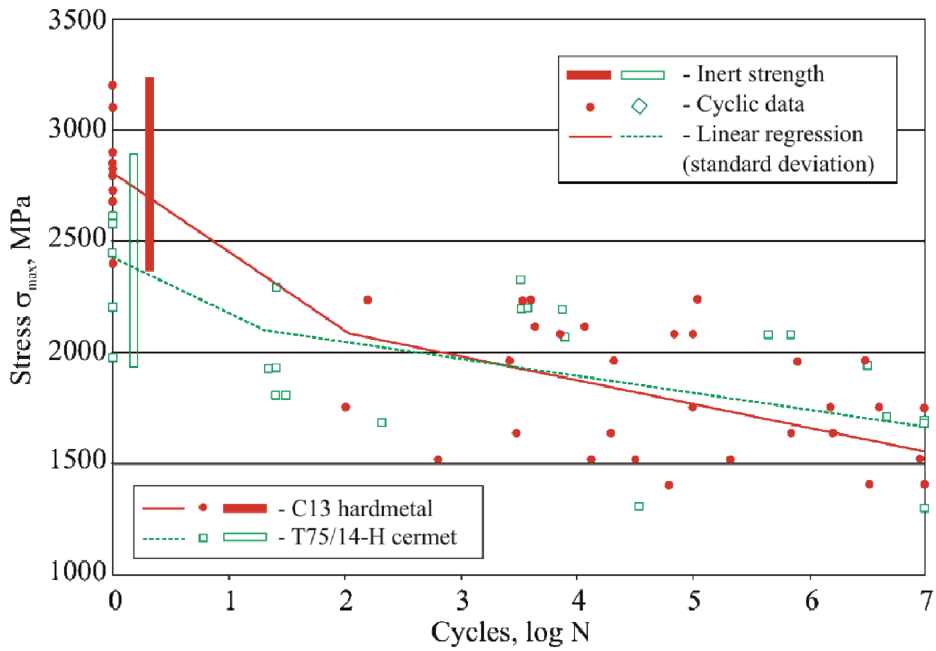

Figure 32 Wöhler plots for hardmetal C13 and cermet T75/14-H

Table 9 demonstrates the blanking performance N/ΔD of composites as opposed to the properties of inserts in the adhesion wear and fatigue testing conditions. The composite with a higher blanking performance possess both a higher adhesive wear resistance and lower fatigue sensitivity (higher resistance to fatigue damage).

Table 9 Blanking performance N/ΔD of carbide composites opposed to their properties (L_1 - adhesive wear resistance, $\Delta S_{3\text{-}7}$ – fatigue sensitivity, $S_1=R_{TZ}$ – transverse rupture strength, S_3 and S_7 – fatigue limit at 10^3 and 10^7 cycles, respectively)

Grade	ΔD, μm	N/ΔD, $\times 10^6$ strokes/mm	L_1, m/mm	$S_1=R_{TZ}$, GPa	S_3, GPa	S_7, GPa	$\Delta S_{3\text{-}7}$, GPa
C13	3.0	160	2100	2.9	2.3	1.5	0.75
T75/14-H	1.8	300	2500	2.4	2.0	1.7	0.30

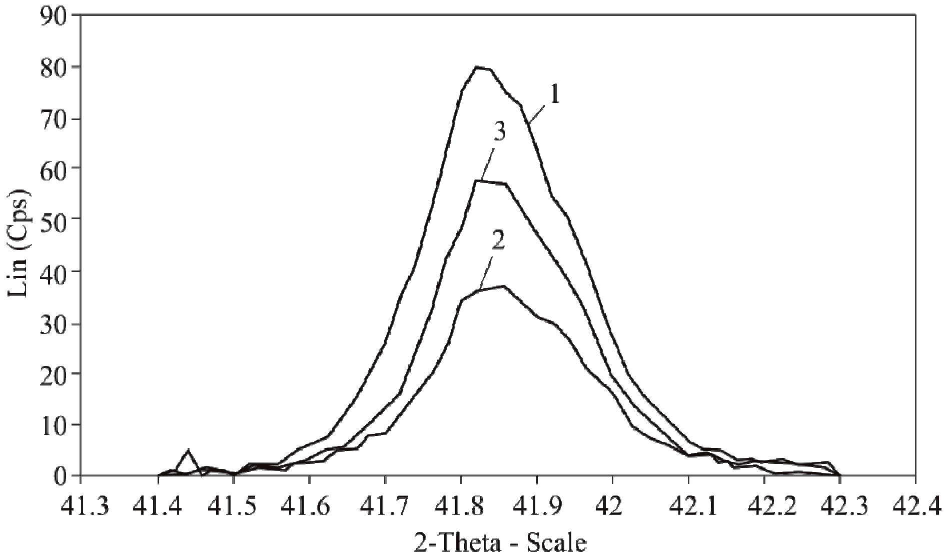

Figure 33 X-ray diffraction patterns (diffractograms) of carbide phases of TiC-based carbide composite: 1 – before testing, 2 – fractured during monotonic loading, 3 – fractured during cyclic loading

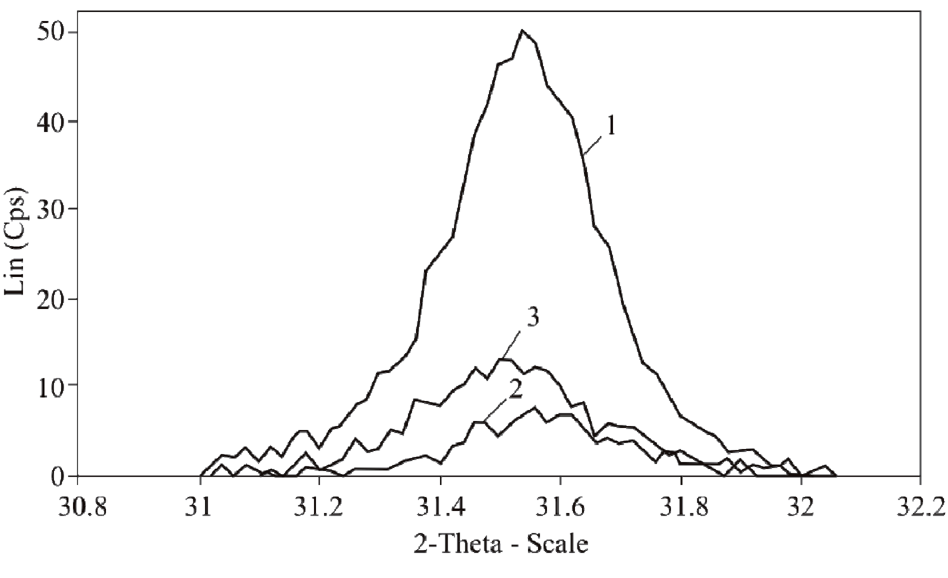

Figure 34 X-ray diffractogram of carbide phases of the WC-based carbide composite: 1 - before testing, 2 - fractured during monotonic loading, 3 - fractured during cyclic loading

As stated by several authors the plastic strain of carbide composite takes place preferably in its ductile binder [77–79]. The XRD measurements performed in the present study on the fractured surfaces of the WC- and TiC-based carbide composites revealed alteration in their diffractograms – a decrease in the intensities and an increase in the broadening of the reflection lines of their carbide phases (Figure 33 and Figure 34). It is known, that such altercations in fine structure refer to local plastic strain [74]. Thus, the ability of carbide composite to absorb fracture energy depends on the plasticity of its both phases.

Table 10 Decrease in the intensity (line peaks) and broadening of X-ray reflection lines from the carbide phases of the composites tested: I_o, I_m, I_c and B_o, B_m, B_c - intensity and broadness before (0), after monotonic (m) and after cyclic (c) loading

Grade	Carbide [line]	Intensity, Lin (Cps)			Decrease in intensity		Broadness B, °			Decrease in broadness,°	
		I_o	I_m	I_c	I_o/I_m	I_o/I_c	B_o	B_m	B_c	ΔB_m	ΔB_c
C13	WC [001]	50	7	12	7	4	0.25	0.32	0.09	0.09	0.07
T75/14-H	TiC [200]	80	36	56	2.3	1.4	0.21	0.26	0.23	0.05	0.02

The results obtained (Figures 33 and 34, Table 10) show that carbide plasticity depends on its composition and loading conditions. Under monotonic loading WC appears to have a higher plasticity compared with TiC (Table 10, I_o/I_m). During cyclic loading (fatigue, blanking) the plasticity of the composite carbide phases decreases – embrittlement occurs. Embittlement depends on the composition of the alloy and is more remarkable for WC-based hardmetal (see Table 10, I_o/I_m and I_o/I_c and line 3 in Figures 33 and 34) compared to TiC-based cermet.

3.2.2 Performance of tool steels with PVD coating

Performance was evaluated in the same conditions as for carbide composites: testing of wear resistance and performance in blanking of sheet steel. Due to revealing of good correlation between blanking performance of carbide composites and their adhesive wear resistance (see section 3.2.1) only adhesive wear of tool steels was under investigation. Blanking performance of tool steel and thin PVD coatings of the highest wear performance was determined at the second stage of research.

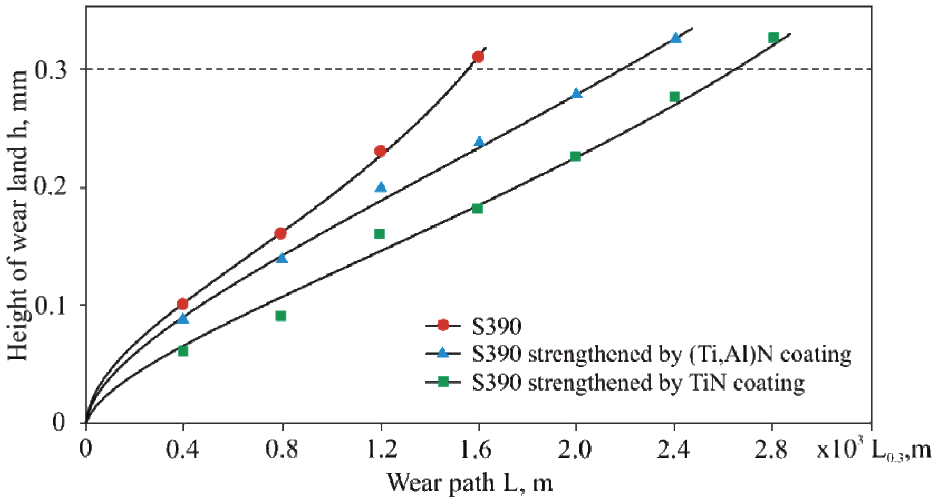

Figure 35 Adhesive wear curves of steel S390 coated by PVD

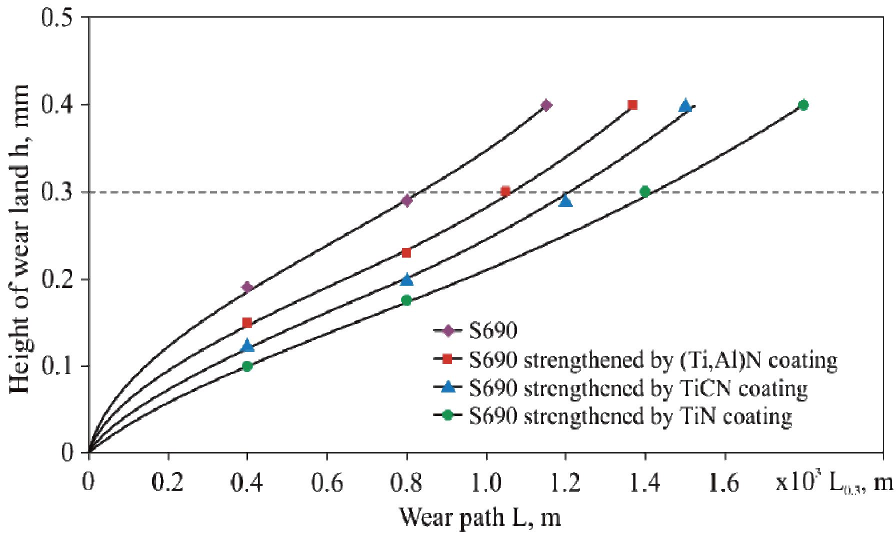

Figure 36 Adhesive wear curves of steel S690 strengthened by PVD coatings

The results presented in Figures 35 and 36 state that the positive effect of strengthening by PVD coatings on adhesive wear resistance depends on both factors – composition of the coating and composition of steel to be strengthened. Steel grade S390, as well as steel grade Vanadis 4E with higher adhesive wear resistance (in relation to S690) ensures also higher strengthening effect (Figure 37) by different coatings. Results refer also to a slight but obvious superiority of TiN coating over (Ti,Al)N ones. Similar results were obtained by other researchers of cutting performance of tools strengthened by TiN and (Ti,Al)N coatings [80–81].

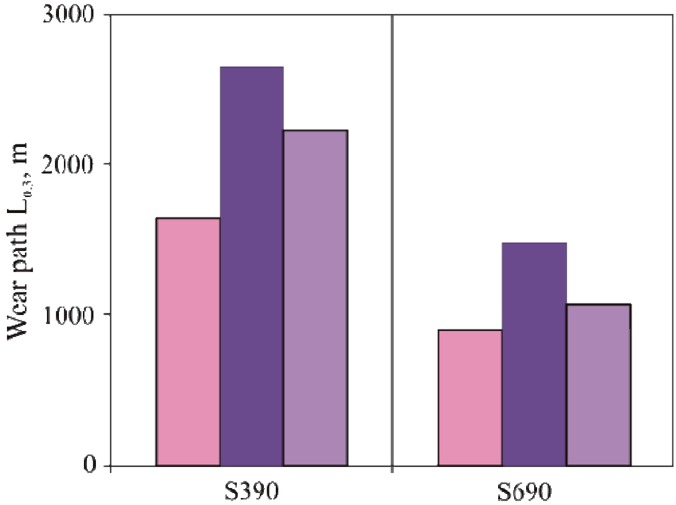

Figure 37 Wear performance of different tool steels (grades S390, S690) strengthened by different depositions: ◻ - without coating, ◼ - PVD TiN coated, ◻ - PVD (Ti,Al)N coated

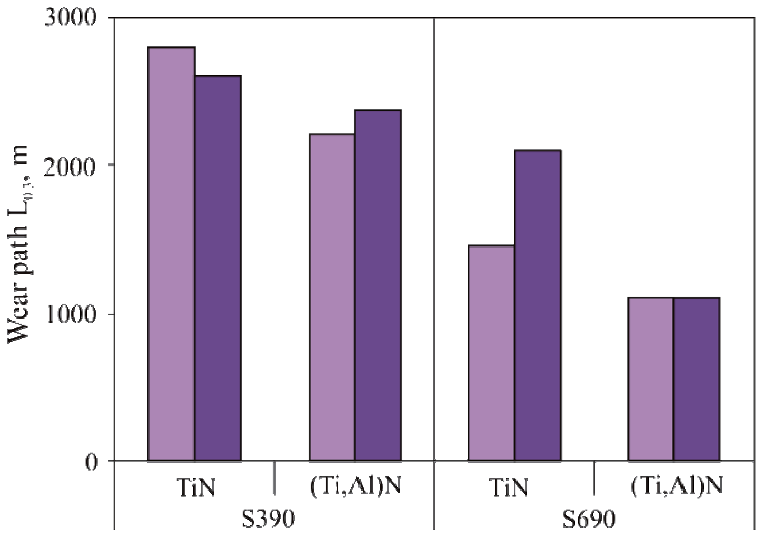

Figure 38 Wear resistance of different tool steels (grades S390, S690) coated by PVD: ◼ - all sides (faces) of the tool are strengthened by coating, ◻ - the face zone is sharpened (coating removed by grinding)

The removal of coating (by sharpening) face zone of the tool does not result in a decrease of wear resistance (Figure 38). It means that effectiveness of a coating strengthening is different in different zones of tool – it is remarkable in flank zone (side wear) and uncertain at face zone. This phenomenon can be related to the differences in stress states and wear mechanism of different faces of the tool.

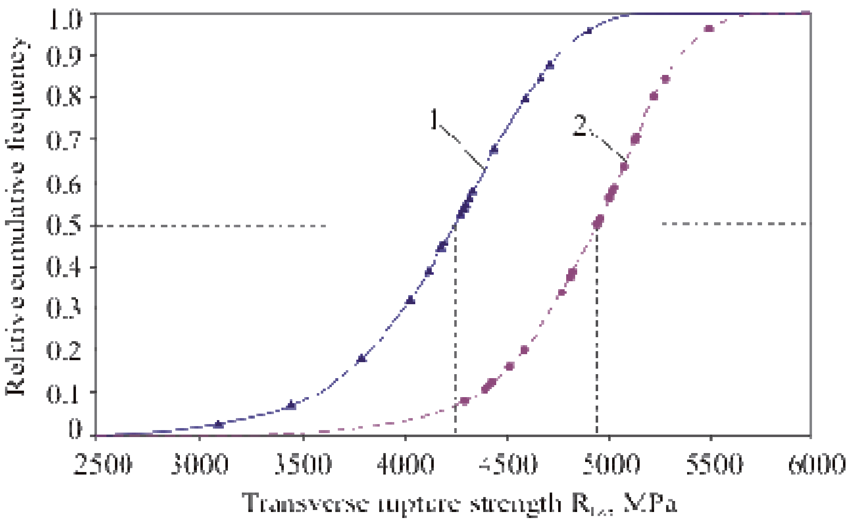

Figure 39 Weibull-plots of transverse rupture strength of tool steels: 1 – strengthened by PVD TiN coating, 2 – uncoated tool

Thin PVD coatings have positive effect on adhesive wear resistance of steels. At the same time, the results of measuring of transverse rupture strength, presented in Figure 39, show that strengthening of tool steel by PVD coating results in a slight decrease of transverse rupture strength.

Table 11 Composition of a 3-row tool (die and punch) for function testing

Position of die	Grade of tool steel	Coating
1	S390	-
2	S390	TiN
3	S390	(Ti,Al)N

The blanking performance of coated with thin PVD coatings tool steels was investigated in the same conditions as during investigation of blanking performance of carbide composites (see section 3.2.1). Durability was evaluated by the side wear of the die $\Delta = \Delta D/2$ after an intermediate service time $N = 0.4\times10^6$ strokes. The composition of 3-position die is presented in Table 11.

In Figures 40 and 41 wear contours of blanking dies and punches made of tool steel of higher performance (S390) and coated by different thin PVD coatings are presented. Strengthening of high-alloy tool steel S390 by TiN and (Ti,Al)N coatings does not result in improvement of its blanking performance. Performance of tool steel (strengthened or not) compare unfavorably to hardmetal by approximately 3 times.

Influence of thin PVD coatings on blanking performance differ from the influence of PVD coating on the adhesive wear performance - obvious effect of coatings on adhesive wear resistance was demonstrated (see Figures 35 and 36). It is also in contradiction with the results of performance in blanking and in adhesive wear conditions of carbide composites (WC-Co hardmetals, TiC-based cermets) demonstrating a good correlation between performance in blanking and adhesive wear resistance (see Figure 30 in section 3.2.1). Such a result can be explained by differences in working conditions during adhesive wear tests (constant loading conditions – turning of soft steel at low speed) and sheet metal blanking (cyclic loading conditions accompanied by adhesive wear and abrasion).

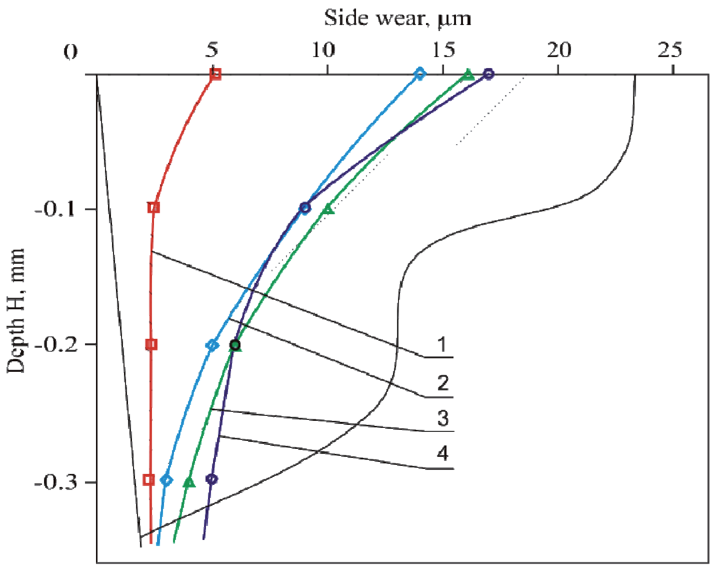

Figure 40 Wear contours of blanking dies (their cutting edges) after blanking of 0.4×10^6 strokes. H – depth of groove in the die, 1 – hardmetal C13 (WC-15Co), 2 – uncoated tool, 3 – tool steel S390 with (Ti,Al)N coating, 4 – tool steel S390 with TiN coating.

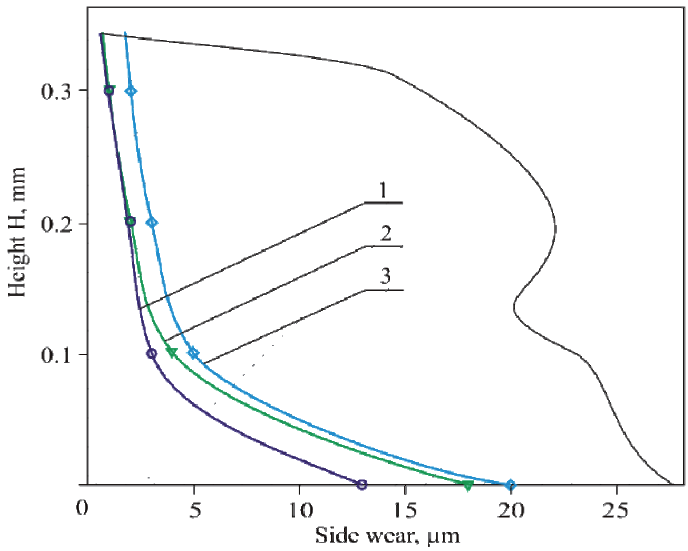

Figure 41 Wear contours of blanking punches made of tool steel coated by PVD after blanking of 0.4×10^6 strokes. 1 – tool steel S390 with TiN coating, 2 – tool steel S390 with (Ti,Al)N coating, 3 – uncoated tool.

In terms of durability of blanking tools PVD coatings used in present research on tool steels seem not to be promising in strengthening of thin electrotechnical sheet metal blanking tools (dies, punches). In terms of prognostication possibilities of durability of tools made from different alloys (carbide composites, tool steels) testing of adhesive wear resistance (in the conditions used in present research) enables assessment of tool life only when materials of similar nature (carbide composites or tool steels) are compared.

4 CONCLUSIONS

The main **conclusions** of the present research are as follows.

Investigation of advanced technologies for enhancing of performance of TiC-based cermets revealed the following:

- gas compression during sintering (Sinter/HIP) has a positive effect on the performance (strength, adhesive wear resistance) of TiC-based cermets;
- hot isostatic pressing (HIP) carried out in two different cycles (Sinter + HIP, also Sinter + Sinter/HIP) is in disadvantage as against one-cycle Sinter/HIP technology.

Study of performance of carbide composites in thin sheet metal blanking as well as in conditions modeling working conditions during blanking (particularly wear and fatigue) has revealed the following:

- the advantage of advanced TiC-based cermet over WC-Co hardmetal both in blanking and adhesive wear conditions (at the similar level of hardness);
- reasonable correlation between blanking performance of carbide composites and their adhesive wear resistance and the similarity of wear (surface failure) mechanism in adhesive wear and sheet metal blanking;
- the higher blanking performance of advanced TiC-based cermet (as against WC-Co hardmetal) results both from its higher adhesive wear resistance and lower fatigue sensitivity;

Study of performance of HSS with PVD coatings in thin sheet metal blanking has revealed the following:

- adhesive wear performance depends both on the composition of the PVD coatings (TiN, TiCN, (Ti,Al)N) and that of tool material (HSS) to be strengthened;
- the PVD coating ensuring enhancing adhesive wear resistance of tool steel induces a slight decrease in strength and an increase in the scatter of strength data;
- strengthening of HSS by PVD coatings does not result in improvement of sheet metal blanking performance of dies and punches (in the condition used in present research).

Revealing of possibilities of utilizing simulating wear tests for assessment of blanking tool performance revealed the following:

- no correlation exists between the durability in blanking and adhesive wear resistance of PVD coated HSS;

- testing of adhesive wear resistance (in the conditions used in present research) enables assessment of tool life only when materials of similar group (carbide composites or tool steels) are to be compared.

The **novelty** of present research is in following:

- The new class of tool materials prospective for metalforming – TiC-based cermets – was studied. Advanced technology for enhancing cermets performance has been investigated.
- Different effect of compression sintering (Sinter/HIP) and sintering and high isostatic pressing (HIP) in different cycles (sintering + Sinter/HIP or Sinter + HIP) on performance characteristics of TiC-based cermets was revealed. It was proved that HIP in two-cycle scheme (sintering + HIP) does not enable improvement in mechanical performance of TiC-FeNi cermet;
- Study of performance of carbide composites in adhesive wear conditions and in blanking revealed advantage of high-performance TiC-FeNi cermet over WC-Co hardmetal (at the same average size of carbides and similar level of hardness);
- It was revealed, that adhesive wear performance of tool steels strengthened by PVD coatings depend both on the composition of the PVD coating and that of tool material to be strengthened. The superiority of TiN coating over TiCN and (Ti,Al)N ones both in wear conditions with prevailation of adhesion and sheet metal blanking was revealed.
- On basis of similarity of surface failure mechanisms occurring during adhesive wear testing and sheet metal blanking possibility of assessment of blanking performance of carbide composite utilizing simple adhesive wear tests was revealed. Similar approach is not relevant when performance of high-alloy tool steels strengthened by PVD coatings in blanking is to be assessed;

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ABSTRACT

Sheet metal blanking tools work in complex conditions – severe abrasive and/or adhesive wear accompanied by high contact stress and mechanical loads of cyclic nature. For better metalforming tool life high-alloy tool steels and ceramic-metal composites (hardmetals, cermets) are utilized. Additional increase in durability of tools can be achieved utilizing thin coatings.

The aim of the current research was to increase the performance of thin sheet metal blanking tools utilizing advanced ceramic-metal composites (TiC-based cermets) and high-performance tool steels strengthened by thin PVD coatings. Research was focused on the following topics: investigation of the effect of advanced sintering technologies (HIP, Sinter/HIP) on performance of TiC-based cermets; study in sheet metal blanking of the performance of advanced TiC-based cermet (produced by elaborated sintering technology and high-alloy tool steels strengthened by PVD coatings; revealing possibilities of utilizing simple simulating wear tests for assessment of blanking tools performance.

According to the research gas compression during sintering (Sinter/HIP) has positive effect on the performance characteristics of TiC-base cermets. At the same time two-cycle scheme (sintering + HIP) does not enable improvement in performance of TiC-based carbide composites. Study of the performance of alternative tool materials (carbide composites) in sheet metal blanking revealed the advantage of advanced TiC-based cermet over WC-Co hardmetal. Reasonable correlation between performance in blanking and adhesive wear resistance was proved. Study of strengthened by PVD coatings tool steels in blanking conditions bring out that the PVD coatings ensuring enhancing of adhesive wear resistance does not improve blanking performance of tools (dies and punches). Adhesive wear performance of tool materials (carbide composites or tool steels) can be utilized for prognostication of blanking tool performance only when materials of similar group (PM composite, high-alloy steel) are compared.

Key words: blanking; carbide composite; cermet; tool steel; adhesive wear; PVD coatings.

KOKKUVÕTE

Lehtmetalli väljalõikestantsimisel kasutatavad tööriistade tööosad (matriitsid, templid) töötavad keerulistes töötingimustes – intensiivne adhesioon- ja/või abrasiivkulumine, millega kaasnevad suured kontaktpinged ja tsüklilised mehaanilised koormused. Väljalõkestantside püsivuse tõstmiseks kasutatakse kõrglegeeritud tööriistateraseid, samuti keraamilis-metalseid komposiitmaterjale – kermiseid ja kõvasulameid. Stantside tööosade püsivust on võimalik täiendavalt suurendada kasutades õhukesi kulumiskindlaid pindeid.

Käesolevat uurimistööd motiveeris tegema vajadus suurendada lehtmetalli väljalõikamisel kasutatavate stantside püsivust sh teritusvahelist ajavahemikku kasutades WC-Co kõvasulamitele alternatiivseid karbiidkomposiite (TiC-baasil kermiseid) ning PVD-pinnetega tugevdatud kõrglegeeritud tööriistateraseid. Teadustöö eesmärgid olid alljärgnevad:

1. Uurida kaasaegsete paagutustehnoloogiate (HIP, Sinter/HIP) võimalusi parandamaks TiC-baasil kermiste toimivust iseloomustavaid omadusi – tugevus, kulumiskindlus.
2. Uurida TiC-baasil karbiidkomposiitide püsivust õhukese lehtterase väljalõike stantsimisel (tavapäraselt kasutatavate WC-Co kõvasulamitega võrreldes).
3. Teha kindlaks PVD pinnete efektiivsust kõrglegeeritud tööriistateraste väljalõikestantside tööosade püsivuse parandamisel.
4. Leida võimalust väljalõikestantside püsivuse prognoosimiseks lihtsaid ja odavaid tribotestimise võimalusi kasutades.

Olulisemad järeldused uurimistöö erinevates aspektides olid alljärgnevad:

1. Uuringud TiC-baasil kermiste kaasaegsete paagutustehnoloogiate valdkonnas näitasid et:
   - survepaagutus (Sinter/HIP) võimaldab suurendada TiC-baasil kermiste paindetugevust ja adhesioonkulumiskindlust;
   - kahetsükliline paagutus järgneva isostaatpressimisega (Sinter+HIP , samuti Sinter + Sinter/HIP) on oma toimelt tunduvalt väiksema efektiivsusega ühetsüklilise survepaagutusega võrreldes
2. Karbiidkomposiitide püsivuse uuringud õhukese lehtterase väljalõikestantsimisel näitasid et:
   - TiC-baasil kermise püsivus võib väljalõkestantsimisel ületada WC-Co kõvasulami püsivust (materjalide kõvaduse sarnase taseme juures;
   - eksisteerib korrelatsioon karbiidkomposiitide püsivuse vahel adhesioonkulumisel ja väljalõikestantsimisel; küllalt sarnane on samuti kulumise iseloom mõlemis võrreldavas töötingimuses;

- TiC-baasil kermise heal tasemel toimivus väljalõikestantsimisel WC-Co kõvasulamitega võrreldes on seletatav nii kermise parema adhesioonkulumiskindlusega kui väiksema väsimustundlikusega.

3. PVD pinnetega tugevdatud tööriistateraste püsivuse uuringud õhukese lehtterase väljalõikestantsimisel näitasid et:

   - adhesioonkulumiskindlus sõltub nii PVD-pindest (TiN, TiCN, (Ti,Al)N kui tugevdatavast tööriistaterasest;
   - PVD pinded, suurendades märkimisväärselt adhesioonkulumiskindlust, samal ajal põhjustavad hübriidmaterjali (teras + pinne) tugevuse vähenemist;
   - PVD pinnete kasutamine ei võimalda suurendada tööriistateraste püsivust lehtterase väljalõikestantsimise tingimustes.

4. Uuringud väljalõikestantside püsivuse prognoosimise valdkonnas lihtsat tribotestimist kasutades võimaldasid järeldada et:

   - Puudub korrelatsioon PVD-pinnetega tugevdatud tööriistateraste adhesioonkulumiskindluse ja nende püsivuse vahel õhukese lehtterase väljalõikestantsimisel;
   - Käesolevas uurimistöös kasutatud tribotestimine adhesioonkulumise prevaleerimise tingimustes võimaldab prognoosida väljalõkestantside püsivust vaid tingimusel, et võrreldatakse samasse materjaligruppi liigituvaid sulameid (karbiidkomposiidid või tööriistateraseid).

PUBLICATIONS

PAPER I

Tšinjan, A., Klaasen, H., Kübarsepp, J., Annuka, H., Influence of sintering techniques on the performance characteristics of steel-bonded TiC-based cermets. Estonian Journal of Engineering, 2009, 15(4), 283 - 292.

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Influence of sintering techniques on the performance characteristics of steel-bonded TiC-based cermets

Aleksei Tšinjan, Heinrich Klaasen, Jakob Kübarsepp and Harri Annuka

Department of Materials Engineering, Tallinn University of Technology, Ehitajate tee 5, 19086 Tallinn, Estonia; jakob.kubarsepp@ttu.ee

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Abstract. This paper analyses the influence of sintering technology (temperature, gas compression during sintering) and heat treatment on the performance of an advanced TiC-based cermet developed for metalforming. The performance was evaluated by adhesive wear resistance, transverse rupture strength and microstructure studies. Optimal technology and parameters, ensuring maximum wear resistance and strength of the TiC-based (carbide) composite, are determined. The positive effect of gas compression during sintering on the performance of TiC-based cermets was revealed. Heat treatment (tempering) that causes no noticeable changes of strength and hardness results in a remarkable decrease of the adhesive wear resistance.

Key words: sintering techniques, cermet, titanium carbide, wear resistance, adhesive wear.

1. INTRODUCTION

Combinations of desirable material properties are encountered in multiphase material structures, such as ceramic and metal composites. Composites on the basis of tungsten carbide, hardmetals, are a success story in terms of applications, particularly those related to tribology. WC-Co hardmetals are the most widely used materials for different wear applications owing to their excellent combination of high wear resistance and strength [[1]]. Deficiency of some specific properties, particularly corrosion resistance and weldability, leads to some restrictions concerning hardmetals and utilization of alternative ceramic and metal composites, e.g. on the basis of titanium carbide.

TiC-based cermets may be successful in some applications, because of their favourable properties – low friction coefficient, fair weldability (owing to their expansion coefficient close to that of steels), remarkable resistance to oxidation, high specific strength and high adhesive wear resistance.

With respect to abrasive wear resistance and strength, TiC-based cermets are usually outperformed by WC-hardmetals [1,2]. However, recent developments in the technology (HIP, sinter/HIP, etc) have created a renewed interest in TiC-based cermets [3,4]. TiC-based cermets, cemented with Ni-Mo alloys, have proven to be appropriate in cutting operations [5]. Steel-bonded carbides − composites "Ferro-Titanit" − have been used in metalforming and in some other special applications [6,7]. The latter have a marked advantage over ordinary hardmetals – they are machinable by conventional methods and become hard and wear resistant as a result of heat treatment. Unfortunately, the relatively low wear resistance (in particular in adhesion) and the modest strength impose restrictions to wider application of such alloys [7].

A series of TiC-based cermets with a Ni-steel binder have been developed at Tallinn University of Technology [8,9]. Grade T75/14 (75 vol% TiC bonded with 14Ni-Fe alloy) that has proved most successful, has demonstrated its superiority over the ordinary WC-base hardmetal (widely used in metalforming) in the blanking of sheet metals [9].

Focus in this paper is on the influence of advanced sintering techniques (vacuum sintering, sinter/HIP, sintering + HIP) and heat treatment on the performance characteristics of the TiC-cermet (grade T75/14). The performance was evaluated by the transverse rupture strength and the adhesive wear resistance.

2. MATERIALS AND EXPERIMENTAL DETAILS

2.1. Materials and technology

The study covers the TiC-based cermet (grade T75/14), a carbide composite with 75 wt% TiC cemented with Ni-steel (14 wt% Ni) of austenitic microstructure. The grade has proven its reliability in metalforming (blanking) applications [9–11].

The alloy was produced by the two-step sintering techniques – presintering in hydrogen (at 550 °C) and final sintering by three different methods: vacuum sintering, sinter/HIP and vacuum sintering + sinter/HIP. At constant sintering time (60 min) sintering temperature and atmosphere (argon-gas) pressure varied from 1400 to 1460 °C and 30–90 bar, respectively. Additionally, the influence of heat treatment (tempering at 200–500 °C) was studied [12,13].

2.2. Testing procedures

Transverse rupture strength (in accordance with the standard ISO 3327, specimen B) and Vickers hardness (in compliance with EN-ISO 6567-1) were used to estimate the mechanical properties.

The wear behaviour of the alloys was studied under adhesive wear conditions. The adhesive wear is featured as a surface failure of very high structure sensitivity. It controls the wear of cemented carbides used for blanking and metalforming operations [10,11]. Adhesive wear tests were performed by turning mild steel (HV30 ≤ 160) at low speed (v < 18 m·min^{-1}). The adhesive wear resistance L_1 was determined as the length of the cutting path, when the wear land (height h) at the tool (specimen) nose achieved the critical value h = 1 mm (Fig. 1).

Twenty tests per composite (produced by different techniques) were performed for mechanical properties and a minimum of three tests for adhesive wear resistance to ensure confidence interval of 10% with probability factor of 95%.

Examinations were complemented by microstructure investigations performed on the scanning electron microscope (SEM) Zeiss EVO MA15. Carbide grain size and binder content were determined by the digital image analysis (Image Pro Plus).

3. RESULTS AND DISCUSSION

3.1. Sintering parameters

The results of mechanical and wear tests presented in Figs. 2 and 3 demonstrate that the properties (performance characteristics) of TiC-based cermets are essentially influenced by sintering parameters. Both, the transverse rupture strength R_{TZ} and adhesive wear resistance, vary approximately 20%,

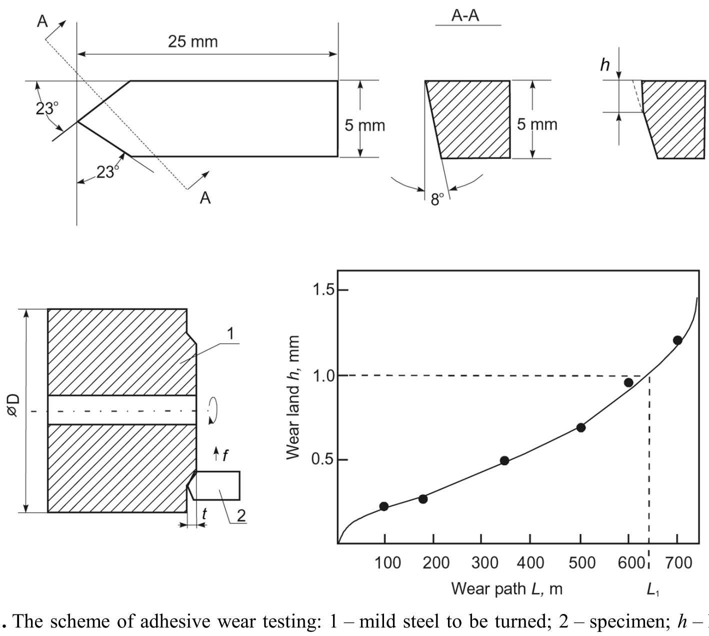

Fig. 1. The scheme of adhesive wear testing: 1 – mild steel to be turned; 2 – specimen; h – height of wear land; L_1 – adhesive wear resistance, L – wear path.

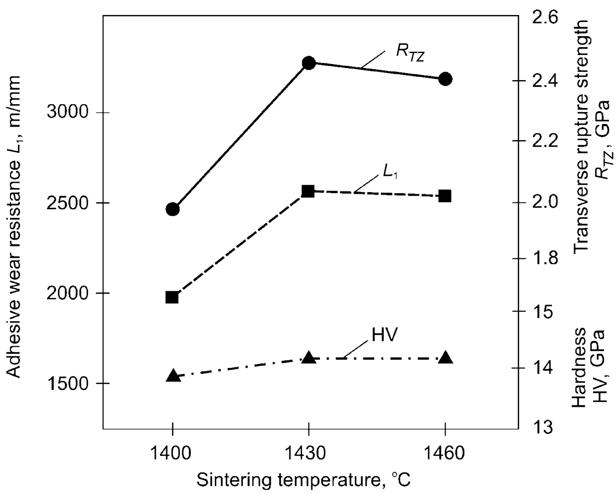

Fig. 2. Influence of the sintering temperature on the performance characteristics of TiC-based cermet T75/14 (compression sintering at p = 60 bar).

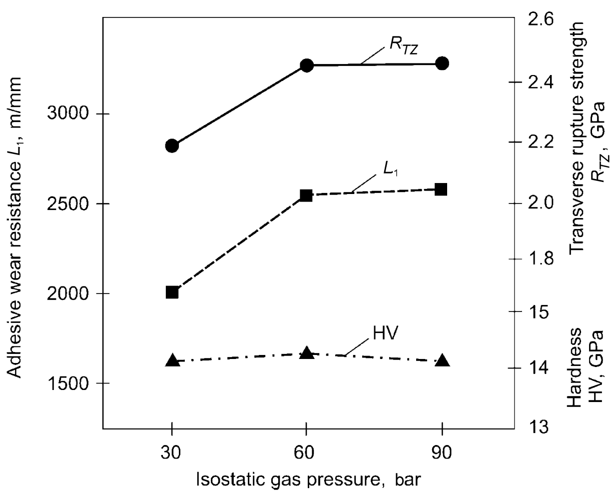

Fig. 3. Influence of the isostatic gas pressure (compression) on the performance characteristics R_{TZ}, and L_1 of TiC-based cermet T75/14 (sintering temperature 1430 °C, sintering time 60 min).

depending on the sintering temperature and gas compression. The relationship refers to the presence of slight maximums (at 1430 °C and 50 bar, respectively).

Results indicate that in contrast to adhesive wear resistance and transverse rupture strength, the hardness (ordinary characteristic of wear resistance) exhibits a low sensitivity to sintering parameters. Such difference in the behaviour of different properties of alloys may be related to differences in their structural sensitivity and stress states (during testing and failure).

3.2. Sintering modes

Figure 4 demonstrates the performance characteristics of the TiC-cermet (grade T75/14), sintered by three different modes: ordinary vacuum sintering, sinter/HIP (SH) and sintering + sinter/HIP (S + SH). Vacuum sintering was performed by optimal parameters – sintering temperature $T = 1430$ °C and vacuum $p < 13$ Pa (10^{-1} mm/Hg) [3,11]. Sinter/HIP was performed in a combined atmosphere – vacuum sintering followed by gas compression at the sintering temperature.

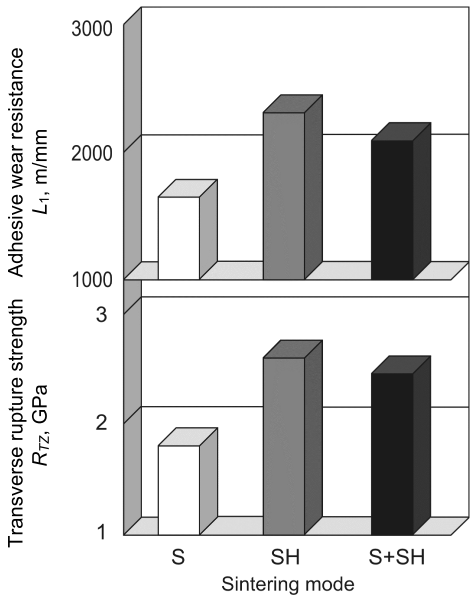

Fig. 4. Performance characteristics of cermet T75/14 sintered by different modes (S – ordinary vacuum sintering, SH – sinter/HIP, S + SH – sintering + sinter/HIP).

The results refer to an obvious positive effect of gas compression during sintering (sinter/HIP) on the performance characteristics of the cermet T75/14 and confirm the results of previous studies concerning the effect of sinter/HIP onto TiC-based cermets [3]. Results also show that the two-cycle sintering mode – vacuum sintering + sinter/HIP-process – is less effective than the one-cycle sinter/HIP process [4,14–19].

3.3. Heat treatment

Ordinarily TiC-based cermets, cemented with Ni-steel, consisting of Ni > 4 wt% possess a stable microstructure (a binder with a stable austenitic structure occasionally including traces of bainite) resulting from sintering. Such composites are not usually subjected to any heat treatment (tempering or normalizing), because heat treatment provides no noticeable improvement in the strength or in the hardness [8,12,20].

This study analysed the effect of tempering at 300–500 °C on such a specific tribological property as adhesive wear resistance. The adhesive wear resistance is a characteristic, relevant in the evaluation of wear performance of alloys applied in metalforming operations [11]. This characteristic is featured by a high structure sensitivity. It means that small changes in the microstructure and stress state of phases result in a remarkable alteration of wear performance [12].

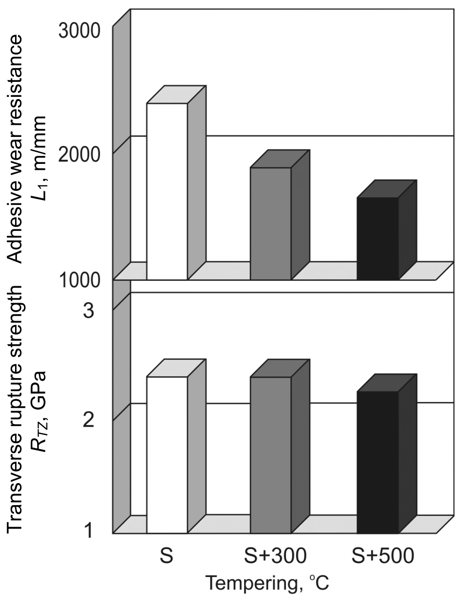

Fig. 5. Performance characteristics of cermet T75/14, tempered at different temperatures.

As seen in Fig. 5, tempering of cermet T75/14 at 300–500 °C does not practically influence the strength, but results in a remarkable decrease (up to 30%) of the adhesive wear resistance.

3.4. Microstructure

The results of SEM studies, presented in Fig. 6, refer to a remarkable influence of sintering techniques on the microstructure of the TiC-based cermet. The microstructure of an alloy, sintered by optimal Sinter/HIP technology (ensuring maximized performance characteristics – strength and wear resistance), is featured by a high homogeneity: uniform distribution of phases, decreased and uniform grain size, reduced contiguity and porosity.

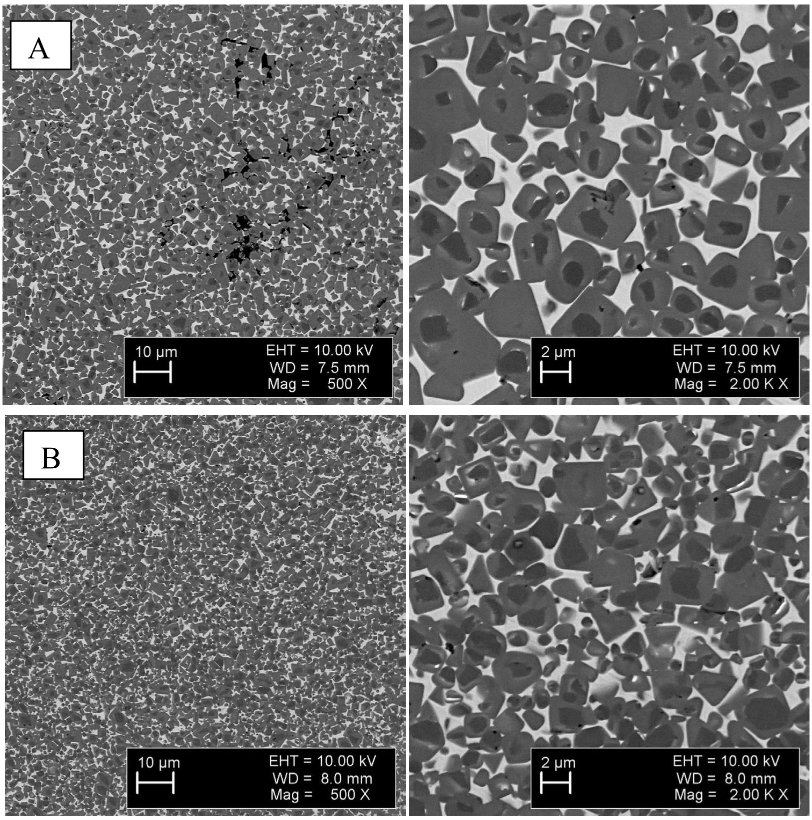

Fig. 6. SEM micrographs of cermet T75/14, sintered by different techniques and differing in the performance characteristics: A – ordinary vacuum sintering technology (R_{TZ} = 1.8 Pa, L_1 = 1600 m/mm); B – optimal technology (R_{TZ} = 2.5 GPa, L_1 = 2300 m/mm).

Heat treatment – tempering at 300–500 °C – induces decrease in the performance characteristics that is remarkable (up to 30%) in the adhesive wear resistance and imperceptible (less than 10%) in the transverse rupture strength. Such kind of behaviour of alloy properties during tempering refer to unnoticeable changes in the structure of the binder or its stress state (decay of the non-uniform austenite binder, relaxation of internal stresses) that influence the characteristics of very high structural sensitivity.

4. CONCLUSIONS

- Focus of the investigation was on the influence of sintering technology (sintering modes, sintering parameters) and heat treatment on the performance characteristics – transverse rupture strength, hardness, adhesive wear resistance – of an advanced TiC-based cermet grade T75/14, developed for metalforming (blanking) applications.
- It was found that gas compression (isostatical gas pressure) during sintering (sinter/HIP-process) has a positive effect on the performance of cermet T75/14.
- Optimal sintering parameters (sintering temperature, gas compression), ensuring maximized performance characteristics (transverse rupture strength and adhesive wear resistance) have been determined.
- Heat treatment of the TiC-cermet T75/14, inducing unnoticeable changes in its binder structure, has a major influence on the properties of high structure sensitivity, particularly on the adhesive wear resistance.
- TiC-based cermets, sintered by the optimal technology that ensures maximized performance characteristics, is characterized by a microstructure of high homogeneity and low porosity.

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Paagutustehnoloogia mõju terassideainega TiC-kermise T75/14 töökindlusele

Aleksei Tšinjan, Heinrich Klaasen, Jakob Kübarsepp ja Harri Annuka

On analüüsitud paagutustehnoloogia (temperatuur, gaasi surve) ja termilise töötlemise mõju terassideainega TiC-kermise T75/14, mis töötati välja TTÜ-s survetöötlemise tööriistade tarvis, töökindluse näitajatele – paindetugevusele, kõvadusele ning adhesioonkulumiskindlusele.

On välja selgitatud optimaalne tehnoloogia, tagamaks materjali maksimaalseid mehaanilisi omadusi ja adhesioonkulumiskindlust. On näidatud, et survepaagutamine võimaldab oluliselt (kuni 25%) tõsta komposiidi T75/14 töökindluse näitajaid – paindetugevust ja adhesioonkulumiskindlust.

Termiline töötlemine ei põhjusta märgatavaid muutusi kermise struktuuris ega mehaanilistes omadustes (kõvadus ja paindetugevus), küll aga halvendab märgatavalt adhesioonkulumiskindlust.

PAPER II

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Performance and failure of carbide composites in different wear conditions

Heinrich Klaasen, Tõnu Roosaar, Jakob Kübarsepp, Aleksei Tšinjan
Department of Materials Engineering, Tallinn University of Technology (TUT)
Ehitajate tee 5, 19086 Tallinn, Estonia
heinrich.klaasen@ttu.ee, jakob.kubarsepp@ttu,ee, tonu.roosaar@tkk.ee, aleksei.tsinjan@antoliv.com

Abstract

This paper describes the wear performance and failure mechanism of some advanced carbide composites (TiC-based cermets and WC-based hardmetals) in different wear conditions. Functional tests were conducted in cyclic loading wear (blanking) and laboratory trials in abrasive, sliding and adhesive wear, complemented by SEM and XRD studies.

Correlation between the blanking performance and adhesive wear resistance of the composites proved fair and similarities were revealed in surface failure morphology. In these conditions, the advanced TiC-cermet was found to be superior over the WC-based hardmetal. It is shown that the wear of a carbide composite starts preferably in the binder and is preceded by local plastic strain taking place in both phases – in the ductile binder and in the brittle carbide.

Key words: cermet, hardmetal, carbide composite, blanking performance, abrasive wear, adhesive wear, sliding wear

1. INTRODUCTION

Carbide composites on the basis of tungsten carbide – hardmetals – are a success story from the viewpoint of their mechanical and tribological properties and spectrum of applications [1]. However, deficiency of some specific properties, particularly corrosion resistance and weldability, restricts the use of hardmetals and alternative ceramic and metal composites, e.g. on the basis of titanium carbide have been developed. Among them TiC-based cermets bonded with Fe/Ni alloy (Ni steels) are still the most promising candidates [2 - 4]. A series of TiC-based cermets have been developed at TUT. One of the most successful so far – the grade T70/14 – has demonstrated its superiority over the ordinary WC- based hardmetal H15 (85 wt% WC) as a tool material for blanking of sheet steels [5, 6].

This paper focuses on the blanking performance of an advanced TiC-cermet – the grade T75/14 (75 wt% TiC cemented with Ni-steel and produced by sinter/HIP technology) [7]. WC-Co hardmetal grade S13 (87 wt% WC) and the ordinary TiC-based cermet grade T70/14 were investigated as reference materials.

Another important aim of the study was to identify any correlation that might exist between blanking performance and wear resistance (in the abrasive, adhesive and sliding wear conditions) on the one hand and between wear-failure mechanisms on the other hand.

2. EXPERIMENTAL

2.1. Materials

The main microstructural characteristics and mechanical properties of the tested composites are presented in Table 1.

The alloys were sintered by two techniques: standard vacuum sintering (for grades T70/14, T75/14 and S13) and sinter/HIP (combined sintering in vacuum + argon gas compression) – for grade T75/14 – H.

Table 1. Structural characteristics and properties (hardness *HV*, transverse rupture strength R_{TZ}, modulus of elasticity *E*, and proof stress $R_{CO.1}$) of carbide composites

Grade	Carbide		Binder		*HV*	R_{TZ}, GPa	*E*, GPa	$R_{CO.1}$, GPa
	wt %	grain size d, μm	Composition	Structure				
T70/14	TiC, 70	2.1	14Ni-steel	Austenitic	1250	2.11	400	2.6
T75/14	TiC, 75	2.0	14Ni – steel	Austenitic	1320	1.80	410	2.9
T75/14-H	TiC, 75	2.1	14Ni- steel	Austenitic	1320	2.40*	410	3.0
S13	WC, 87	1.8	Co(W)		1300	2.80	590	2.8

*after sinterhipping

2.2. Testing procedures

The procedure of the durability functional test resembled that in service, i.e.– blanking of grooves into electrotechnical sheet steel (with a hardness of 150 *HV* and a thickness of 0.5 mm) using a three-position die reinforced with the three different composites to be investigated, mounted on an automatic mechanical press [5, 6].

The wear resistance, i.e. the blanking performance of carbide composites, was evaluated by the measurement of the side wear of the die Δ (increase in diameter) after an intermediate service time $N=0{\cdot}5 \times 10^6$ strokes, as N/Δ (lifetime in strokes per 1 mm of the side wear Δ). The intermediate service time 0.5×10^6 corresponded to the time between two consecutive prophylactic sharpenings used in the exploitation of blanking dies [7]. The side wear was measured using the measuring machine STRATO 9 – 166 in fixed environmental conditions (constant room temperature and humidity of 40%) as an average of 4 – 6 measurements.

Abrasive wear tests were performed using the rubber-rimmed rotary machine (modified ASTM G65 – 94 method) as follows: abrasive-quartz sand (amount 3 kg, particle size 0.1 – 0.2 mm, hardness *HV* 1100), velocity of wheel 0.24 m/s, testing time 10 min, and load 3 N. The wear was estimated as the volume lost in mm^3.

A special method was used for adhesive wear tests (elaborated for the evaluation of blanking performance), namely turning of mild steel (HV=160) at low speed v <12 m min^{-1}, in which surface adhesive failure generally prevails [5]. The wear rate was determined as the height of the wear land *h* at the tool (specimen) nose after the specific length of the cutting path *L*. The adhesive wear resistance L_1 was determined as the length of the cutting path *L* when the height of the wear land *h* achieved the critical value of *1* mm. The critical height *h* = 1 mm of the wear land corresponded to the onset of the accelerated wear.

Sliding wear tests were performed in accordance with the ASTM standard B611 – 85 procedure, without abrasive at a loading F= 40N and a wear length L= 4000 m. The volumetric wear rate was calculated as $\Delta V= \Delta m/\rho$, where Δm is the average (of three specimens) mass loss and *p* is the density of the alloy.

Examinations were complemented by SEM and XRD investigations performed on the scanning electron microscope JEOL JSM 840A and the diffractometer Bruker D 5005, respectively. The line broadening and intensity of X-ray reflections from the composite phases were determined in the XRD studies [8].

3. RESULTS AND DISCUSSION

3.1. Wear performance

Results of functional wear tests (conducted as the blanking of grooves into the sheet steel) are shown in Fig. 1 as wear contours Δ-*H* (side wear Δ depending on the depth *H* from the cutting edge of the die). During testing ($N=5 \times 10^5$ strokes) of the die (three position die reinforced with the sample cermets/hardmetals), neither fracture nor brittle macrochipping of cutting edges was detected.

Cutting edges became blunt as a result of uniform wear. The wear contours (Fig. 1) and the side wear data for the dies tested demonstrate the obvious superiority of the advanced TiC-based cermet over hardmetal S13 and cermet T70/14.

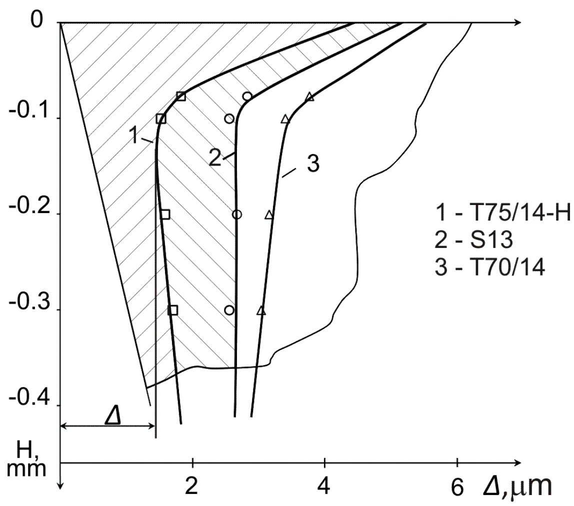

Fig.1. Wear contours of carbide tool (die) edges – side wear Δ *after blanking of* $5{\cdot}10^5$ *strokes. H – deph of groove measured from cutting edge.*

The advanced TiC-based cermet demonstrated a blanking performance exceeding that of the ordinary composites up to 1.5 – 2 times.

Figure 2 shows the blanking performance *N/Δ* of carbide composites investigated (TiC-based cermets, hardmetal) opposed to their response as inserts in the abrasive, sliding and adhesive wear conditions.

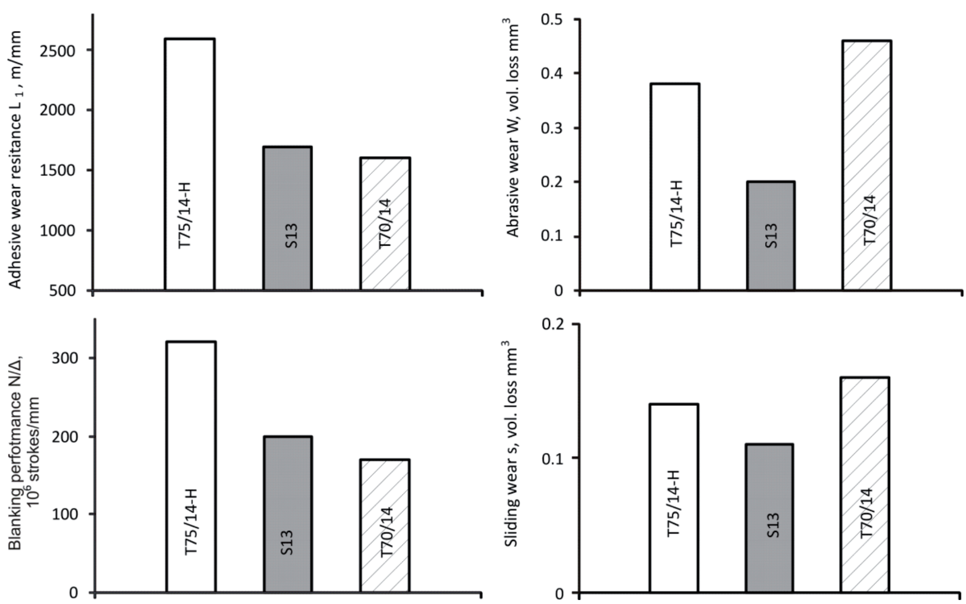

Fig. 2. Blanking performance *N/Δ* of carbide composites and their response as inserts in adhesive, abrasive and sliding wear conditions.

In terms of abrasive wear resistance, both of the TiC-based cermets were considerably worse (up to three times) than the hardmetal.

As stated in previous research, the abrasive wear of carbide composites is controlled by the resistance to elastic and plastic strain and depends first on the properties of the carbide phase (modulus of elasticity) [9]. At approximately equal resistance to plastic strain (measured by the proof stress), the resistance of hardmetals to elastic strain (measured by the modulus of elasticity) exceeds that of TiC-cermets by a factor of 1.6.

In general, the results obtained in the sliding wear trials and in the abrasive tests are in agreement, i.e. they demonstrate the advantage of hardmetals over TiC-based cermets (although their superiority is somewhat less obvious).It also highlights the role of the carbide phase of alloys (their strength and rigidity) to withstand surface failure during sliding and abrasive wear.

Concerning adhesive wear performance of carbide composites, a fair correlation was found between the adhesive wear resistance and the blanking performance. Results demonstrate the superiority of the advanced TiC-based cermet T75/14-H over hardmetal S13 (by a factor ~1.5).

SEM studies of worn carbide composite surfaces confirm the results described above. They demonstrate that surface failure mechanisms occurring during adhesive wear and sheet metal blanking are similar: in both cases surface failure (removal of material) appeared first in the binder phase (Fig. 3). The distinctive nature of the worn surfaces confirms that binder extraction prevails in both cases. In contrast to adhesive wear, surfaces worn during abrasive and sliding wear do not show this distinction.

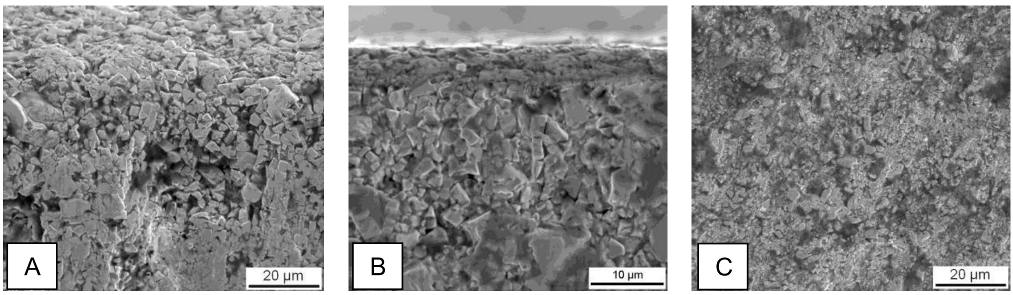

Fig. 3. SEM image of cemented carbide S13 surface after blanking (A), after adhesive wear testing (B) and abrasive wear testing (C).

3.2. Microstructural aspects of carbide composite surface failure (wear)

As reported in previous studies devoted to the wear mechanisms of carbide composites, the removal of material during wear has a selective nature and starts preferably in the binder phase by microcutting (sliding wear, abrasive wear) and extraction (adhesive wear) [5,6, 9 - 11]. After removal of the binder, carbides lose their steady protective envelope (generating favourable stresses in the carbide), resulting in a drop of their resistance to brittle failure (subsurface microfailure) [9].

The resistance of the carbide phase to brittle failure is controlled by the level of the elastic strain energy transmitted to the surface during wear (and storing at the tips of the flaws of the composite microstructure)[9, 12]. The elastic strain energy may relax either by origin and the propagation of microcracks or by a local plastic strain. The resistance of the composite carbide phase to brittle fracture depends therefore on its ability to undergo the local plastic strain (to absorb the fracture energy by the local plastic strain).

As stated, the plastic strain of a carbide composite takes place preferably in its ductile binder [13]. The XRD measurements performed in this study on the worn surfaces of the WC- and TiC-based composites revealed alterations in their difractograms – a decrease in the intensities and an increase in the broadness of the reflection lines of their carbide phases (Figs. 4 and 5). These alterations refer to changes in the fine structure (dispersity of micrograins and density of dislocation network) of the carbide phase induced by their plastic strain taking place during the wear-loading [8, 14].

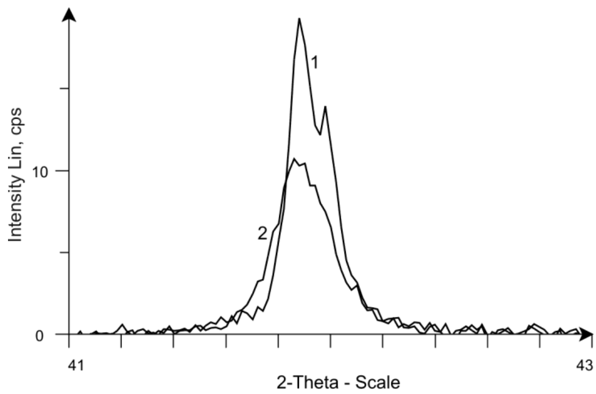

Fig. 4. XRD pattern of the carbide phase of the TiC-based cermet: 1 – before testing; 2 – after sliding wear testing

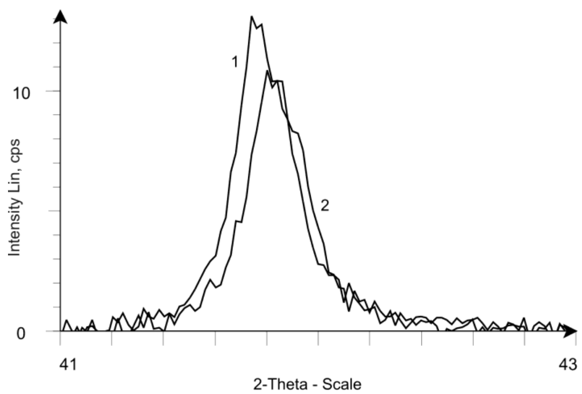

Fig.5. XRD pattern of the carbide phase of the TiC-based cermet: 1 – before testing; 2 – after adhesive wear testing.

Changes in the fine structure of the carbides in the composites tested appear to depend on the alloy's composition and wear conditions – they are higher (see Table 2) in the hardmetal (than the TiC-based cermet) and lower in composites subjected to the adhesive wear (in relation to the abrasive and sliding wear). These differences in changes in the fine structure (featuring plastic strain) of the carbide during the wear-failure refer to the dependence of carbide plasticity (measure I_o/I and B/B_o) on the stress state.

Table 2. Decrease in intensity I and increase in the broadness B of the lines of X-ray reflections from the carbide phases of the composites tested in the abrasive, sliding and adhesive wear conditions.
I_o, I_w, I_s, I_A – intensity, B_o, B_w, B_s, B_A - broadness before (O) and after abrasive (W), sliding (S) and adhesive (A) wear testing, respectively.

Grade	Carbide, line	Decrease in intensity, times			Increase in broadness, times		
		I_o/I_w	I_o/I_s	I_o/I_A	B_w/B_o	B_s/B_o	B_A/B_o
T75/14-H	TiC[200]	1.4	1.3	1.1	1.3	1.2	1.1
S13	WC[001]	1.5	1.5	1.2	-	1.3	1.1

As stated, during the adhesive wear of composites, material removal occurs preferably by extraction (with prevalation of tension stresses) and therefore failure plasticity is less compared to the abrasive and sliding wear when shear stresses (microcutting) prevail [12, 15].

The results received in this study confirm our previous findings concerning alterations in the fine structure of carbides subjected to cyclic loading (fatigue). [14] They refer to the ability of the carbide phase in a composite to undergo plastic strain during loading and wear and to the dependence of this phenomenon on the stress state (loading-wear conditions) and alloy composition.

CONCLUSIONS

- Wear performance and mechanism in different wear conditions, including cyclic loading (functional tests in blanking of sheet metals) of an advanced TiC-based cermet and that of hardmetal, were compared and as a result, the advantage of the cermet was revealed in blanking and adhesive wear conditions.
- Reasonable correlation between the blanking performance of carbide composites and their adhesive wear resistance and similarity in the surface failure morphology was found.
- The surface failure of a carbide composite during wear starts preferably in the binder and is preceded by local plastic strain, taking place in both alloy phases – in the ductile binder and in the brittle carbide .
- The failure plasticity of a carbide (TiC, WC) depends both on the alloy composition and the stress state and is more remarkable for the hardmetal and in the wear conditions where shear stresses prevail, particularly in the abrasive and sliding wear.

Acknowledgements

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PAPER III

Klaasen, H., Kübarsepp, J.,_Tšinjan, A., Adoberg, E., Vainola, V., Performance of tool steels strengthened by PVD coatings, EURO PM2010 Proceedings Vol 3: EURO PM2010, Florence, Italy, European Powder Metallurgy Association, 2010.

PERFORMANCE OF TOOL STEELS STRENGTHENED BY PVD COATINGS

Heinrich Klaasen, Jakob Kübarsepp, Aleksei Tšinjan, Eron Adoberg, Vello Vainola
Department of Materials Engineering, Tallinn University of Technology (TUT)

Ehitajate tee 5, 19086 Tallinn, Estonia

Abstract
This paper describes the performance of some metalforming tool steels strengthened by different PVD-coatings. The performance was evaluated by adhesion wear resistance and transverse rupture strength. Wear tests were performed by a special metal cutting method that consisted of turning of mild steel at low speed (simulating wear in sheet metal blanking). It was shown that the performance of strengthened steel depends on both the composition (properties) of the coating and the composition (properties, in particular wear resistance) of the steel to be coated. The optimum coating and the steel ensuring an enhanced performance was found to show that strengthening results in remarkable increase in wear resistance at a slight decrease of strength.

1. INTRODUCTION

Carbide composites (hardmetals and cermets) have been successful as powder metallurgy wear resistant materials. Their applicability is somewhat limited by the geometric size of the parts and cost. For these reasons hard coatings (TiN, TiCN, etc.) have been widely used [1-3]. PVD-coatings have proven to be prospective for cutting tools and abrasive wear applications [3-6]. Information concerning prospects of coatings, in particular PVD coatings for tools working in conditions with prevalence of adhesion wear (in particular blanking tools), is comparatively restricted [7].

The present study is focused on the effect of different PVD coatings for strengthening of tools working in adhesion wear conditions (metalforming, particularly blanking tools). The high-alloy steels (HSS-) widely used in metalforming as well as some carbide composites WC – Co and TiC – FeNi were studied as tool materials.

2. EXPERIMENTAL DETAILS

Composition and mechanical properties of tool materials (steels, carbide composites) are presented in Table 1.

Grade	C	Cr	Mo	W	V	Other	HRA	R_{TZ} , MPa
S690 S390 VAN4E	1.3 1.3 1.4	4.0 4.5 4.7	5.0 4.5 3.5	6.0 10 -	6.5 4.8 4.0		87 87 86	4000 4500 4300
H13	77WC		-	-	-	13Co	89	2900

Table 1. Composition (wt%) and properties (Rockwell A hardness, transverse rupture strength) of the investigated tool materials

The coatings (TiN, TiCN, TiAlN) were deposited in the arc plating PVD-unit PLATIT-750, using Lateral Rotating ARC-Cathodes (LARC) technology. The temperature was 450°C and coating thickness was 3.4 μm.

The strength of alloys was determined as transverse rupture strength in accordance with the standard ISO 332/7 (specimen “B”). Twenty specimens (per alloy) were tested and statistically treated to obtain reliable Weibull distribution curves (failure probability curves) and to ensure a confidence interval of <4% with a probability factor of 98%.

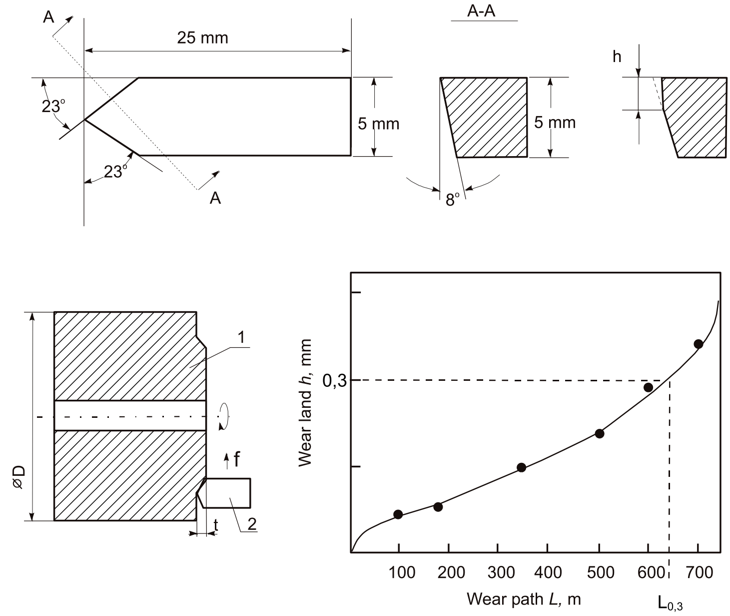

Fig.1 The scheme of cutting adhesive wear testing: (1) mild steel to be turned, (2) specimen: *h* - height of wear land, *L* - cutting path, $L_{0.3}$ - adhesive wear resistance

A special cutting method (Fig.1) was developed and used for adhesive wear tests. It consists of turning of mild steel (150 HV) at low speed, simulating the wear of a blanking die (wear with prevalence of adhesion). In previous works an excellent correlation between the wear resistance determined by this method and the wear of blanking dies was revealed [8, 9]. The wear resistance $L_{0.3}$ was determined as the length of the cutting path when the height of the wear land at the specimen (tool) nose achieves 0.3 mm. The critical wear of 0.3 mm corresponds to the critical wear (side wear) of the blanking tool to be removed during sharpening [8]. The wear was examined on two types of specimens (cutting tools): first, on a tool with a strengthened (by PVD deposition) face and second, on a tool without a strengthened face (PVD deposition removed by sharpening). Minimum of three specimens were tested to ensure the confidence interval of 10% with the probability factor of 95%.

3. RESULTS AND DISCUSSION

3.1. Adhesive wear

Fig. 2 demonstrates the wear curves *“h – $L_{0.3}$”* of HSS steel S690 strengthened by different PVD-coatings (compared with unstrengthened steel). Results presented refer to an obvious effect of PVD strengthening. Performance (wear resistance) $L_{0.3}$ of strengthened steels exceeds that of unstrengthened steels up to 1.4 times (from 800 – 900 m up to 1400 m). Results obtained refer to a slight but obvious superiority of the TiN coating over TiCN and TiAlN ones.

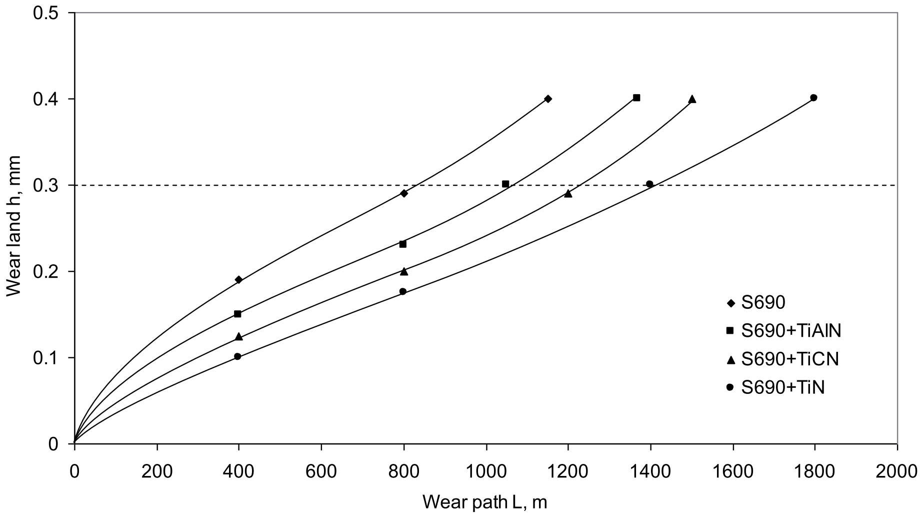

Fig. 2 Adhesive wear curves “h – L” of steel S690 strengthened by different PVD coatings.

Results presented in Figs. 2 and 3 allow us to state that the effect of strengthening (by PVD coating) depends on both factors – on the composition (properties) of the coating and surprisingly on that of steel (its wear resistance) to be strengthened. Steels S390 and VAN4E with higher adhesive wear resistance (as compared to S690) ensure also higher strengthening effect.

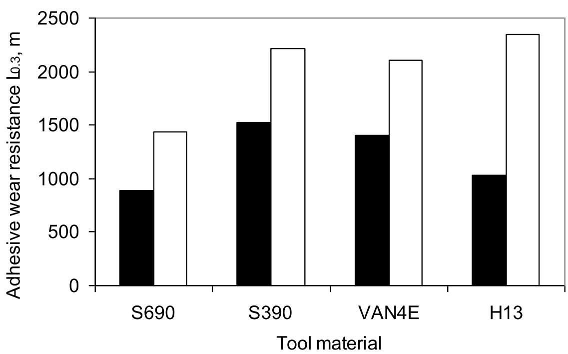

Fig.3 Wear resistance of different tool materials strengthened by TiN PVD coating. ■ unstrengthened ☐ strengthened (and sharpened by grinding) tool

The results presented above (Figs. 2, 3) were obtained using “sharpened” specimens (specimen with removed by grinding coating at the face zone of tool).

The “additional” effect of a strengthened face is demonstrated in Fig. 4. Surprisingly it can be stated that the performance of a tool with an unstrengthened face (with removed coating at face) exceeds remarkably that of a strengthened (by PVD coating) one.

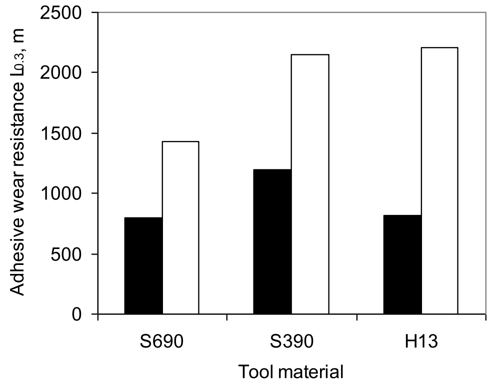

Fig.4 Wear performance of different tool materials strengthened by the TiN PVD coating. ■ strengthened tool □ strengthened tool with sharpened face (removed coating)

This phenomenon can be explained by differences in the stress states of face-flank surfaces of the tool and high brittleness of the coating deposited. It can be shown that in the face zone close to the cutting edge (nose of a tool) prevail tension stresses (bending). These bending stresses induce microchipping of the brittle TiN coating deposited on the face. The failure product – debris of TiN – act as abrasive inducing acceleration of wear.

3.2. Mechanical properties

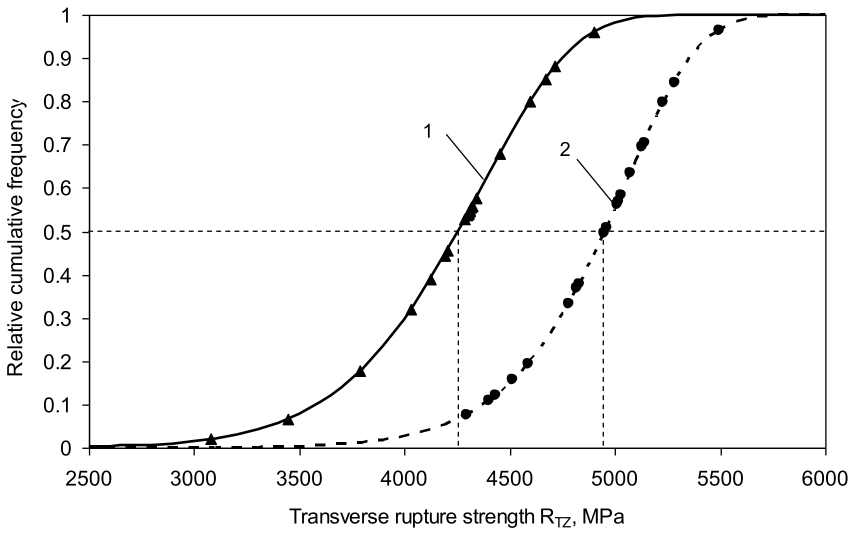

Fig.5 Distribution curves (Weibull plots) of transverse rupture strength

(1) – tool strengthened by the TiN coating; (2) – unstrengthened tool

The results of strength trials (transverse rupture strength) are presented in the form of Weibull plots, Fig.5 (failure probability curves) [10].

The results obtained show that strengthening of a tool steel by PVD coatings (TiN) results in a slight decrease of strength. It is interesting to note that the decrease in strength is accompanied by an increase in the scatter of strength data.

It should be emphasized that high performance and reliability of an alloy depends on both – the mean inert strength and its fracture resistance stability (scatter of failure data). A high scatter in strength refers to high fragility (presence of structural defects) and to inclination of the alloy to untimely failure.

CONCLUSIONS

1. The performance (adhesive wear resistance and transverse rupture strength) of some metalforming tool materials, strengthened by PVD coatings has been investigated and the optimum coating revealed.

2. It was shown that the performance depends both on the composition of the coating and on that of the tool material (its wear resistance) to be strengthened.

3. It was revealed that sharpening of the tool (removal by grinding of the coating at the face zone of the tool) results in an additional increase of wear resistance.

4. The optimum coating ensuring maximum enhancement of the wear resistance of a tool induces a slight decrease in strength characteristics

ACKNOWLEDGEMENTS

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PAPER IV

Klaasen, H., Kübarsepp, J., Tšinjan, A., Sergejev, F., Performance of carbide composites in cyclic loading wear conditions, Wear, 2011, 271, 837-841.

PERFORMANCE OF CARBIDE COMPOSITES IN CYCLIC LOADING WEAR CONDITIONS

H. Klaasen, J. Kübarsepp, A. Tšinjan, F. Sergejev

Department of Materials Engineering, Tallinn University of Technology,
Ehitajate tee 5, 19086, Tallinn, Estonia

Abstract

Comparative analysis of the durability of an advanced TiC-based cermet developed in TUT with the WC-based hardmetal (widely used in metalforming) in cyclic loading wear conditions – in sheet metal blanking – has been made and the fracture mechanism specified. Adhesive wear resistance as well as fatigue endurance were tested, complemented by SEM and XRD studies. The superiority of the advanced TiC-based cermet over the hardmetal was revealed, related to its higher resistance to adhesive wear and fatigue damage (lower fatigue sensitivity).

1. Introduction

Cermets are ceramic-metal composites which consist of the ceramic phase and the metal binder. Tungsten carbide (WC) and titanium carbide (TiC) based ceramic and metal composites (carbide composites) are the most known cermets. WC-based cermets – hardmetals are the most widely used composites in different wear applications owing to their excellent combination of high wear resistance and strength, as well as toughness [1, 2]. TiC-based cermets (with Ni-alloy or steel binder) have proven successful in some applications because of their high specific strength (low density), high adhesive wear resistance, good weldability and improved resistance to oxidation [3, 4].

Application of carbide composites (hardmetals, cermets) enables service life of tools and wearing machine parts to be prolonged. These materials are mainly used in service conditions where high wear resistance either in abrasive conditions or at elevated temperatures (high speed cutting) is required. Carbide composites are not so often used in non-cutting (metalforming) operations owing to complicated service conditions where severe wear (particularly adhesive wear) is accompanied by high mechanical loads of cyclic and dynamic nature. In such conditions primarily special cold or hot working steels or hardmetals with increased binder content have been successfully used [1, 5].

Tallinn University of Technology (TUT) has developed a series of TiC-based cermets, particularly tool materials for plastic forming of metals. One of the most successful cermets – grade T70/14 (70 wt% TiC cemented with Ni-steel) – has proven itself as a tool material in blanking of sheet metals [6, 7].

The present paper is focused on the study of performance in cyclic loading wear conditions of an advanced (with improved properties) cermet – grade T75/14-H produced by optimized technology (Sinter/HIP, heat treatment) [8, 9]. As reference materials, the WC-based hardmetal grade C13 (87 wt% WC) widely used in metalforming and the ordinary TiC-based cermet grade T70/14 (70 wt% TiC) were also under investigation.

2. Experimental

2.1. Materials

The main microstructural characteristics and mechanical properties of tested carbide composites are presented in Fig.1 and Table 1. Fig.1 shows the microstructures of the composites with carbide fraction of ~80 vol. %. The microstructure of WC-composite (grade C13) consists of WC-grains mainly of angular shape embedded in the binder phase. The shape of TiC grains is more rounded.

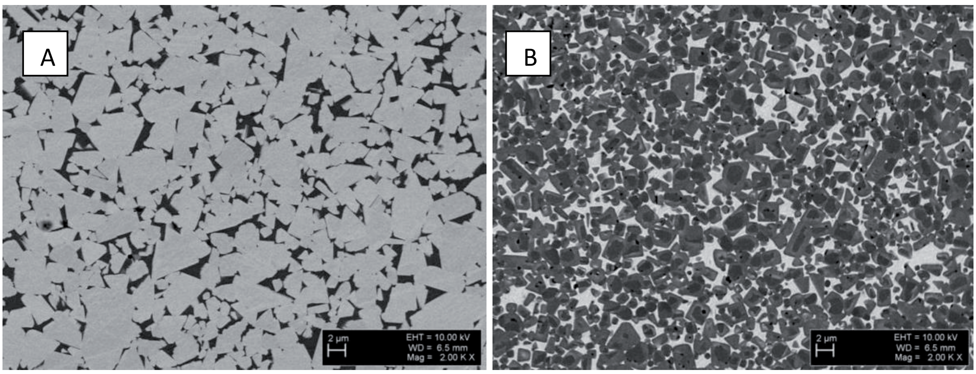

Fig. 1 SEM images of investigated carbide composites
A – WC-based hardmetal (C13), B – TiC-based cermet (T75/14-H)

The alloys were sintered by two techniques: ordinary vacuum sintering (hardmetal grade C13 and cermet T 70/14) and by combined sintering in vacuum + argon gas compression (cermet grade T75/14-H) – developed for TiC-based cermet sinter/HIP technology [8, 9].

Table 1. Structural characteristics and properties (hardness *HV*, transverse rupture strength R_{TZ}, proof stress $R_{CO.1}$) of carbide composites tested

Grade	Carbide, wt%	Mean grain size, µm	Binder	*HV*, *GPa*	R_{TZ}, *GPa*	$R_{CO.1}$, *GPa*
C13	WC, 87	1.8	Co (W)	13.0	2.9	2.8
T70/14	TiC, 70	2.1	Fe (14Ni)	12.8	2.2	2.4
T75/14-H	TiC, 75	2.0	Fe (14Ni)	13.6	2.4	2.8

2.2 Testing procedures

Durability (blanking performance) trials were carried out as functional ones in blanking on an automatic press of grooves into electrotechnical sheet steel (see Fig.2) by a 3-position die reinforced with alloys presented in Table 1 [6, 7]. Durability was evaluated by the side wear of the die ΔD (increase in diameter D) after an intermediate service time N=0.5 · 10^6 strokes (as $N/\Delta D$) corresponding to the time between two consecutive prophylactic sharpenings used in the exploitation of blanking dies [7]. The side wear was measured using the measuring machine STRATO 9-166 in fixed environmental conditions (constant room temperature of 20 ± 2°C and relative humidity of 50...60%) as an average of five measurements.

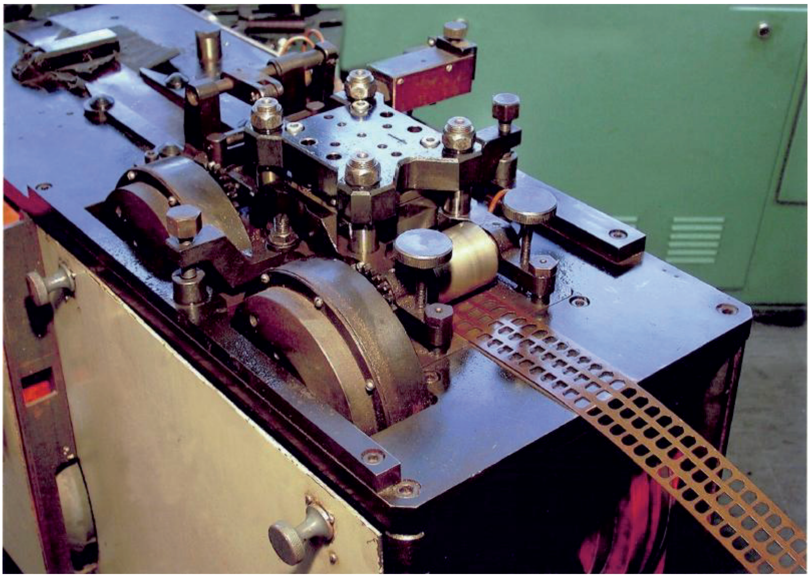

Fig.2 Durability testing of carbide composites in 3-position blanking die, mounted on the automatic press

The wear was studied in cutting adhesive wear conditions [7]. The wear resistance L_1 was determined as the cutting path (by turning mild steel) when the track at the nose of a specimen (tool) exceeded 1 mm.

Fatigue tests resembled those of three point bending fatigue – fatigue of specimen of 5 x 5 x 17 mm under sinusoidally alternating transverse bending load at the stress ratio $R = 0.1$ and frequency f = 30 Hz, up to 10^7 loading cycles [10 - 13]. The resistance to fatigue damage was characterized by the factor of fatigue sensitivity –intensity in the decrease of strength with an increase in the loading cycles from $N_3 = 10^3$ to $N_7 = 10^7$ as $\Delta S_{3\text{-}7}$.

Examinations were complemented by SEM and XRD studies of micro- and fine structure, performed on the electron microscope JEOL JSM 840A and diffractometer Bruker D5005, respectively. Changes of line intensities of X-ray reflections from composites phases (line peaks) and their broadening (both characterizing changes in fine structure) were determined in the XRD studies [14, 15].

3. Results and discussion

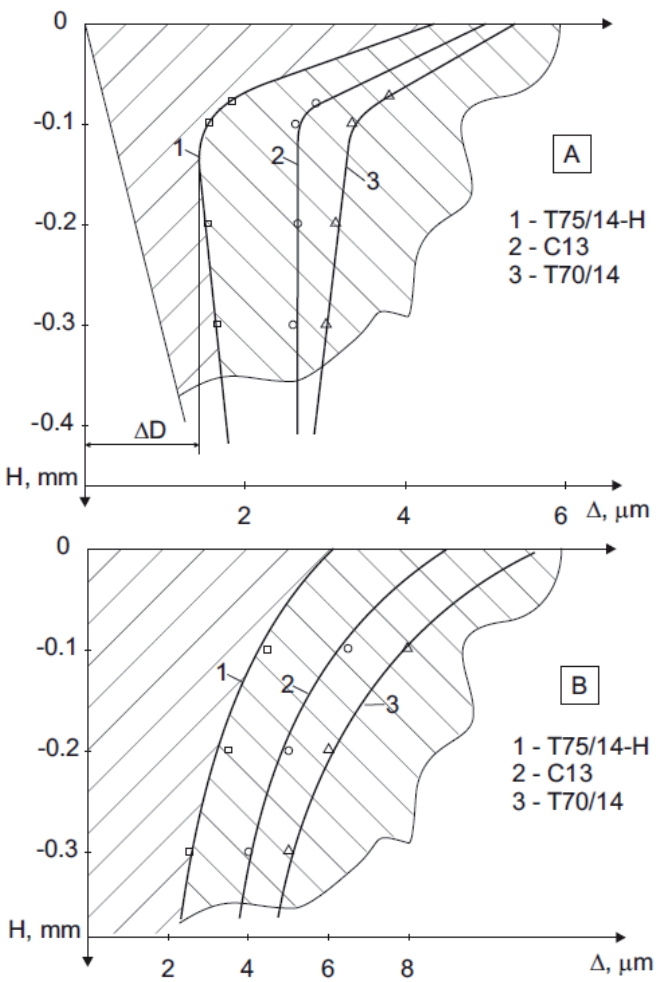

Fig. 3 Wear contours of blanking tools (their cutting edges)
A – side wear ΔD_1 of dies, B – side wear ΔD_2 of punches

Results of functional wear tests are shown in Fig. 3 as wear contours $\Delta D - H$ (side wear ΔD depending on the depth H from the cutting edge of the tool). The wear contours both of the die and punch refer to a superiority of the advanced TiC-based cermet T75/14-H over the hardmetal and cermet T70/14. The blanking performance $N/\Delta D$ ($N = 0.5 \cdot 10^6$ strokes) of the advanced composite exceeds that of ordinary composites by a factor of 1.5 ... 2.

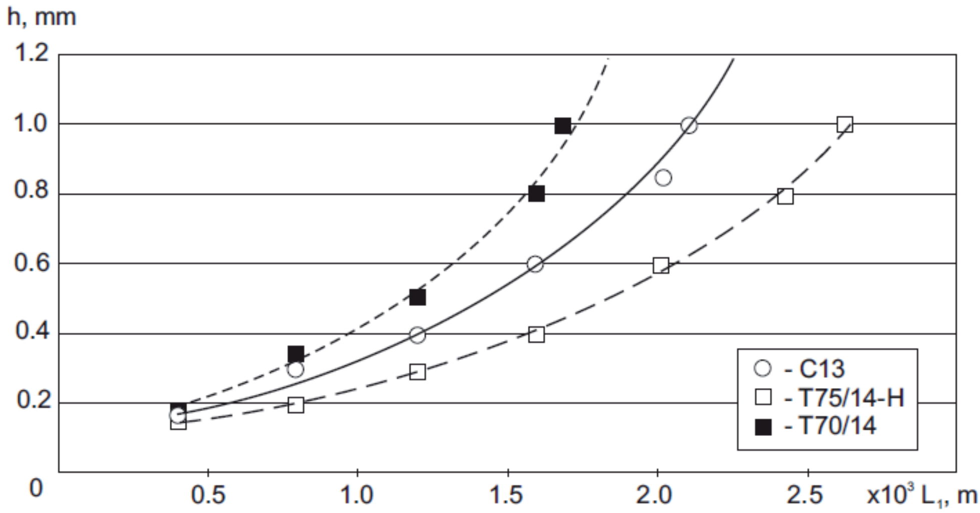

Fig. 4 Adhesive wear curves *h-L* of the carbide composites investigated

The results of the adhesive wear test (as wear kinetic curves *h* – *L*) are presented in Fig. 4. They confirm the results of the blanking trials – the superiority of the developed TiC-based cermet (grade T75/14- H) over WC-based hardmetals (grade C13). These results refer to the existence of a correlation between the composite's blanking performance and its adhesive wear resistance.

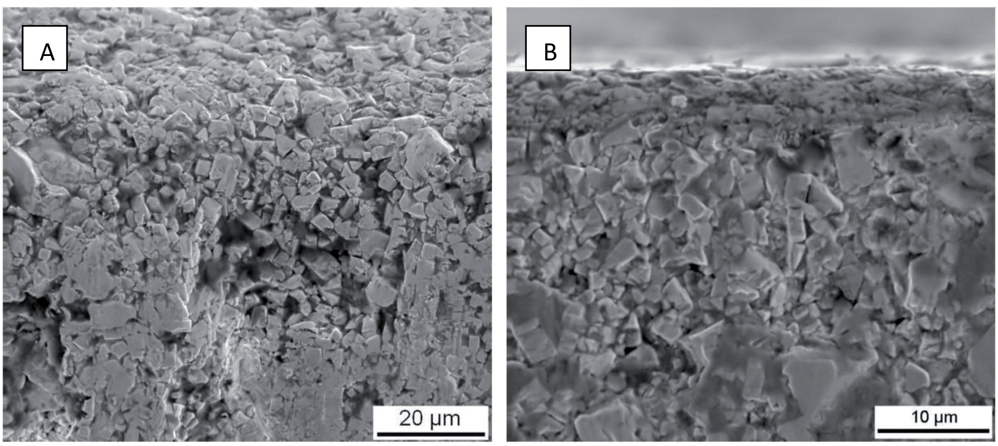

Fig. 5 SEM image of the cemented carbides surface microstructure after blanking (A) and testing of adhesive wear (B)

SEM studies of worn carbide composites surfaces confirm the conclusion stated above (see Fig. 5). They show that surface failure mechanisms occurring during adhesive wear and blanking are similar – in both cases failure (removal of material) appeared first in the binder. The distinctive nature of the worn surfaces confirms that binder extraction prevails in both cases [9, 10].

After removal of the binder (by extrusion) the carbide phase loses the protective envelope (fracture generating favourable compression stresses in the carbide), resulting in a drop of resistance to brittle failure (cracking/microcracking) [16]. Thus, the increase in the composite's resistance to adhesive wear (removal of binder) results in the increase of its resistance to brittle failure (microchipping, cracking).

Fig. 6 shows the results of fatigue trials – the Wöhler plots of the advanced TiC-based cermet T75/14-H and WC-based hardmetal C13. The tested carbide composites exhibit an obvious decrease in strength *S* with an increase of loading cycles *N* during fatigue testing – they possess fatigue sensitivity (the slope *S* – *N*).

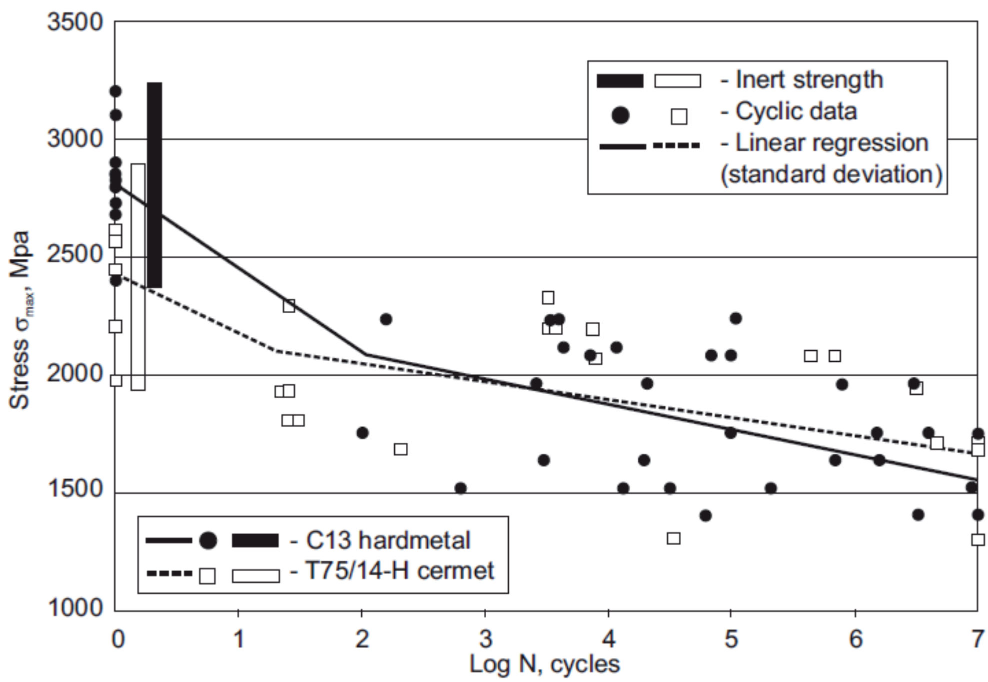

Fig. 6 Wöhler plots for hardmetal C13 and cermet T75/14-H

Although the transverse rupture strength (R_{TZ} = S_I = 2.9 GPa) and cyclic strength at low cycles (N<10^3) of the WC hardmetal exceed those of the TiC-cermet (R_{TZ} = 2.4 GPa), the fatigue limits at $N > 10^5$ show an opposite result – the superiority of the cermet T75/14-H over the hardmetal (S_7=1.7 GPa against 1.5 GPa). It means that the fatigue sensitivity, i.e the intensity in the decrease of strength with the increase in loading cycles (the slope S-N of the Wöhler plot) of TiC-cermet, is lower.

Table 2. Blanking performance $N/\Delta D$ of carbide composites opposed to their properties (L_1 - adhesive wear resistance, $\Delta S_{3\text{-}7}$ – fatigue sensitivity, $S_1=R_{TZ}$ – transverse rupture strength, S_3 and S_7 – fatigue limit at 10^3 and 10^7 cycles, respectively

Grade	ΔD, µm	$N/\Delta D$ X 10^6 strokes/mm	L_1, m/mm	$S_1=R_{TZ}$, GPa	S_3, GPa	S_7, GPa	$\Delta S_{3\text{-}7}$, GPa
C13	3.0	160	2100	2.9	2.3	1.5	0.75
T75/14-H	1.8	300	2500	2.4	2.0	1.7	0.30

High fatigue sensitivity refers to a remarkable fatigue damage of an alloy during cyclic loading (fatigue, blanking of a sheet metal). Table 2 demonstrates the blanking performance $N/\Delta D$ (N – loading, blanking cycles, ΔD- side wear of blanking tool) of composites, as opposed to the properties of inserts in the adhesion wear and fatigue testing conditions. Results refer to a correlation between the blanking performance of the carbide composite and its adhesive wear resistance on the one hand and its fatigue sensitivity on the other hand. The composite with a higher blanking performance T75/14-H possesses both a higher adhesive wear resistance and lower fatigue sensitivity (higher resistance to fatigue damage).

The resistance of a material to a brittle failure is controlled by the level of the elastic strain energy transmitted during loading (monotonic, cyclic – fatigue, blanking) and storing preferably at the tips of flaws in the composite microstructure [16, 17]. The elastic strain energy storing in a material during loading (fatigue, blanking wear) may be released either by the formation and propagation of cracks or by local plastic strain [16]. The resistance of a carbide composite to brittle fracture depends therefore on its ability to undergo the local plastic strain (to absorb fracture energy by plastic strain).

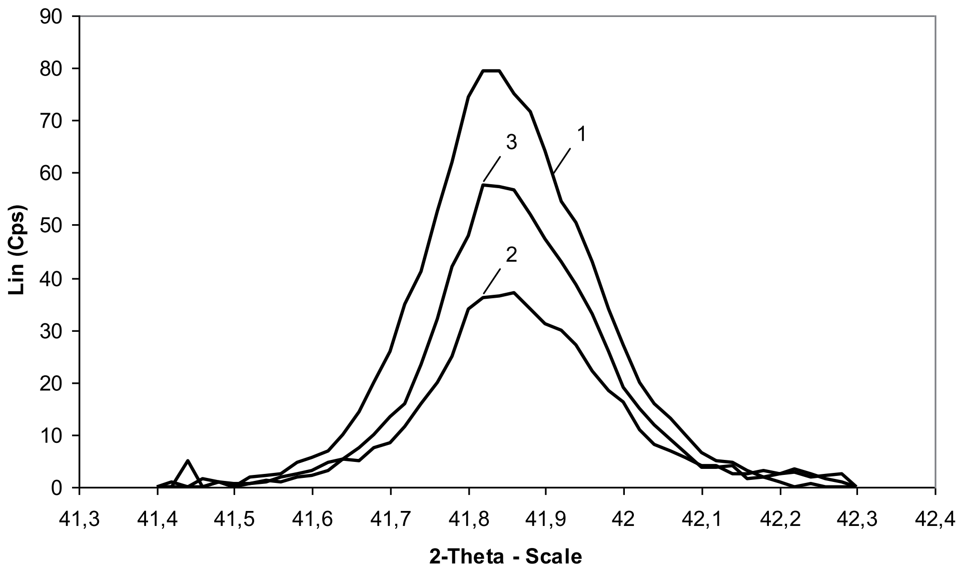

Fig. 7 X-ray diffraction patterns (diffractograms) of carbide phases of the TiC-based composite:

1 – before testing (etalon), 2 – fractured during monotonic loading; 3 – fractured during cyclic loading.

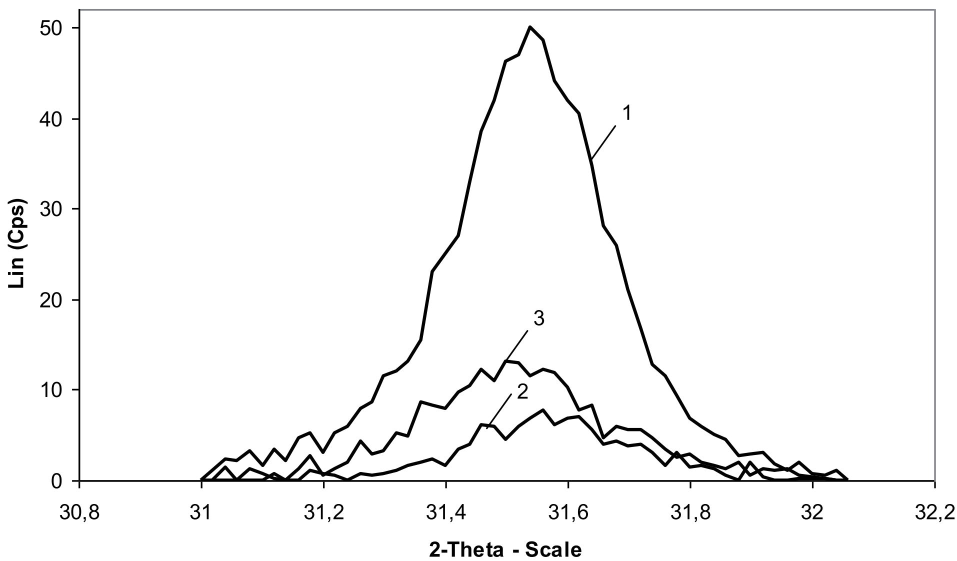

Fig. 8 X-ray diffractogram of carbide phases of the WC-based carbide composite: 1 – before testing, 2 – fractured during monotonic loading, 3 – fractured during cyclic loading

As stated, the plastic strain of a carbide composite takes place preferably in its ductile binder [11, 16]. The XRD measurements performed in the present study on the fractured surfaces of the WC-based and TiC-based composites revealed alterations in their diffractograms – a decrease in the intensities (line peaks) and an increase in the broadness of the reflection lines of their carbide phases (Figs. 7 and 8). These alterations refer to changes in the fine structure (dispersity of micrograins and density of dislocation network) of the carbide phases [14, 15]. It is known that such alterations in fine structure refer to local plastic strain [10]. Thus, the ability of the carbide composite to absorb fracture energy depends on the plasticity of its both phases – the ductile binder and the "brittle" carbide.

Table 3. Decrease in the intensity (line peaks) and broadening of X -ray reflection lines from the carbide phases of the composites tested: I_o, I_m, I_c and B_o, B_m, B_c – intensity and broadness before (0), after monotonic (m) and after cyclic (c) loading

Grade	Carbide [line]	Intensity, Lin (Cps)			Decrease in intensity		Broadness B, °			Decrease in broadness, °	
		I_o	I_m	I_c	I_o/I_m	I_o/I_c	B_o	B_m	B_c	ΔB_m	ΔB_c
C13	WC [001]	50	7	12	7	4	0.25	0.34	0.32	0.09	0.07
T75/14-H	TiC [200]	80	36	56	2.3	1.4	0.21	0.26	0.23	0.05	0.02

The results obtained (Figs.7, 8 and Table. 3) show that carbide phase plasticity depends on its composition and loading conditions. Under monotonic loading conditions WC appears to have a higher plasticity compared with TiC (Table 3, I_o/I_m). During cyclic loading (fatigue) the plasticity of the composite, carbide phases (WC and TiC) decreases – an embrittlement takes place.

The intensity in embrittlement depends on the composition of the alloy (carbide composite) and is more remarkable for a WC-based hardmetal (see Table 3 I_o/I_m and I_o/I_c and line 3 in Figs. 7 and 8) compared to TiC-based cermets. The embrittlement (decrease in the plasticity of the composite / its phases) results in a decrease of strength with an increase of loading cycles during fatigue – an increase in the fatigue sensitivity of an alloy.

Thus, the superiority of the advanced TiC-based cermet (over the ordinary WC-based hardmetal), its higher blanking performance, may be related mainly to two properties – to higher adhesive wear resistance and higher resistance to fatigue damage – higher resistance to embrittlement during cyclic loading (to its lower fatigue sensitivity).

4. Conclusions

1. Performance in cyclic loading conditions – results of the functional test in the blanking of sheet metals and fatigue bending tests – of an advanced TiC-based cermet and that of a WC-based hardmetal (used in metalforming) were compared. As a result, the advantage of the cermet was found.
2. Reasonable correlations between the blanking performance (resistance to the side wear of the blanking tool) of the composite and its adhesive wear resistance and similarity in the surface failure morphology was found.
3. It was shown that the resistance of the carbide composite to fatigue failure during cyclic loading (blanking of sheet metal) is characterized by its fatigue sensitivity – intensity in the decrease of fatigue strength with an increase in loading cycles.
4. The failure of the carbide composite during monotonic and cyclic loading (bending fatigue, blanking of sheet metals) is preceded by local plastic strain taking place in its both phases – in the ductile binder and in the brittle carbide.
5. During cyclic loading (fatigue, blanking) the plasticity of the carbide composite (its phases) decreases and an embrittlement takes place.
6. The higher blanking performance of the TiC-based cermet (in relation to a hardmetal) results from its higher adhesive wear resistance and its lower fatigue sensitivity (as a result of its higher resistance to embrittlement).

Acknowledgements
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Figure captions

Fig. 1 SEM images of investigated carbide composites
A – WC-based hardmetal (C13), B – TiC-based cermet (T75/14-H)

Fig. 2 Durability testing of carbide composites in 3-position blanking die, mounted on the automatic press

Fig. 3 Wear contours of blanking tools (their cutting edges)
A – side wear ΔD_1 of dies
B – side wear ΔD_2 of punch

Fig. 4 Adhesive wear curves *h-L* of the carbide composites investigated

Fig. 5 SEM image of cemented carbide's surface microstructure after blanking (A) and testing of adhesive wear (B)

Fig. 6 Wöhler plots for hardmetal C13 and cermet T75/14-H

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Fig.8 X-ray diffractogram of carbide phases of the WC-based carbide composite:
1 – before testing, 2 – fractured during monotonic loading, 3 – fractured during cyclic loading

PAPER V

Tšinjan, A., Klaasen, H., Kübarsepp, J., Adoberg, E., Talkop, A., Viljus, M., Performance of tool steels strengthened by PVD coatings in adhesion and cyclic loading wear conditions, Proceedings of EURO PM2011 Congress and Exhibition, Barcelona, Spain, European Powder Metallurgy Association, 2011

PERFORMANCE OF TOOL STEELS STRENGTHENED BY PVD COATINGS IN ADHESION AND CYCLIC LOADING WEAR CONDITIONS

Aleksei Tsinjan, Heinrich Klaasen, Jakob Kübarsepp, Eron Adoberg, Adolf Talkop and Mart Viljus*

Department of Materials Engineering, Tallinn University of Technology (TUT)

Ehitajate tee 5, 19086, Tallinn, Estonia

**AS Norma, Laki Str. 14, 10621, Tallinn, Estonia*

Abstract

This paper describes the wear performance of some metalforming tool steels strengthened by different PVD coatings (TiN, TiAlN). The performance was evaluated by adhesive wear resistance and durability in the conditions of cyclic loading wear (blanking of sheet steel). Adhesion wear was performed by a turning (cutting) method (simulating wear of blanking tools) while durability tests were performed as functional ones – as tool wear during blanking of sheet metal in production conditions by means of a blanking die. It is shown that in adhesive wear conditions the performance depends on both the composition (properties) of the PVD coating and on that of the tool material to be deposited. No correlation between the durability (resistance to the side wear of the blanking tool strengthened by PVD coating) and adhesive wear resistance was revealed.

1. INTRODUCTION

Carbide composites (hardmetals and cermets) have been successful as powder metallurgy high wear resistant materials [1]. Their applicability is somewhat limited by the geometric size of the parts and the cost. For these reasons hard coatings (TiN, TiCN, etc.) based on transition metal nitrides, carbides and carbonitrides are widely used to protect material against wear and corrosion [2–4 etc]. Due to their advanced characteristics, such as high microhardness, chemical inertness, high wear resistance, these coatings, particularly PVD coatings, are employed in various machining and abrasion applications [5–7 etc]. Information concerning prospects of coatings, in particular PVD coatings for tools working in conditions with prevalence of adhesion wear (in particular sheet metal blanking tools), is comparatively restricted [8-10].

The present study is focused on the effect of PVD coatings for strengthening of tools working in adhesion wear conditions (metal forming, particularly blanking tools) [11, 12]. The high-alloyed steels (HSS-steels) widely used in metal forming were studied as tool materials.

2. EXPERIMENTAL DETAILS

Composition and mechanical properties of the tool materials (steels) tested are presented in Table 1.

Steel Grade	C	Cr	Mo	W	V	HRA	R_{TZ}, MPa
S690	1.3	4.0	5.0	6.0	6.5	87	4000
S390	1.3	4.5	4.5	10	4.8	87	4500

Table 1. Composition (wt%) and properties (Rockwell hardness HRA, transverse rupture strength R_{TZ}) of the tool materials investigated.

Thin coatings (TiN, (Ti,Al)N) were deposited in the arc plating PVD-unit PLATIT-750 using the lateral rotating ARC-Cathodes (LARC) technology. The temperature was 450°C and coating thickness was ~ 3 μm.

A cutting method (Fig. 1) was developed and used for adhesive wear tests [11, 13]. It consists of turning of mild steel (HV 150) at low speed (simulating the wear of a blanking die in the conditions of prevalence of adhesion). In previous works an excellent correlation between the wear resistance determined by this method and the wear of blanking dies was revealed [11, 12].

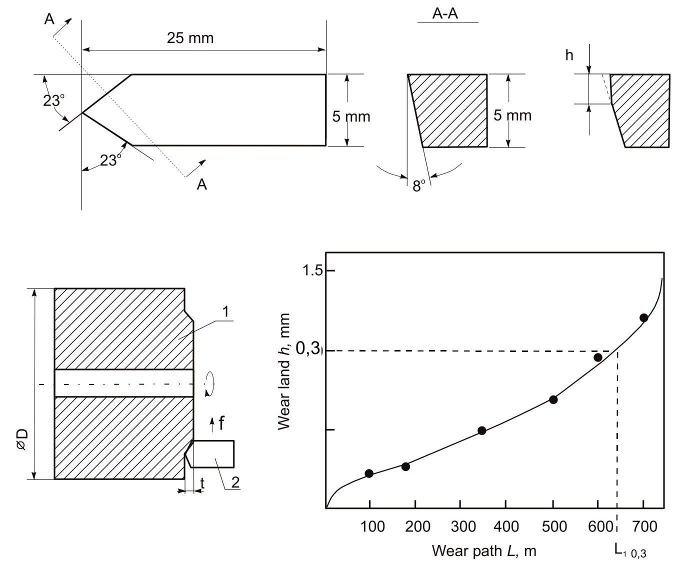

Fig. 1 The scheme of cutting adhesive wear testing: (1) mild steel to be turr :) specimen: *h* – height of wear land, *L* – cutting path, $L_{0.3}$ – adhesive wear resistance [13]

The adhesive wear resistance $L_{0.3}$ was determined as the length of the cutting path when the height of the wear land at the specimen (tool) nose achieves 0.3 mm.

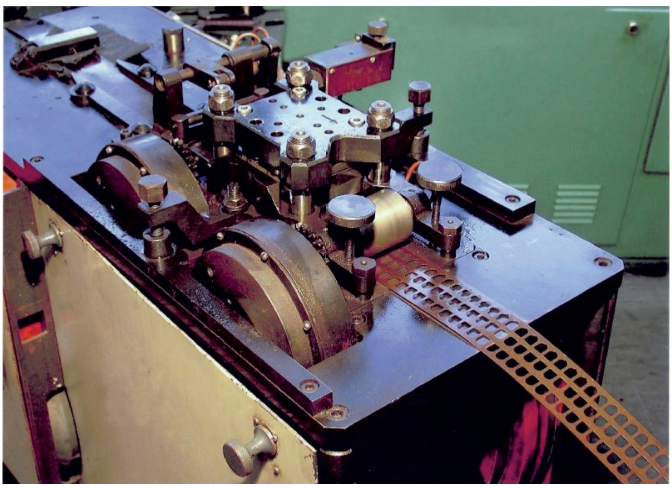

Fig. 2 Durability testing of carbide composites in a 3-position blanking die mounted on the automatic press [11]

Durability (blanking performance) trials were carried out as functional ones (see Fig. 2) in blanking on an automatic press of grooves into electrotechnical sheet steel (with hardness HV = 150, proof stress $R_{p0.2}$ = 1600 N/mm^2, tensile strength R_m = 3200N/mm^2 and thickness of t = 0.5 mm) by a 3-position die reinforced with tool steel S390 with and without coatings (see Table 2). Durability was evaluated by the side wear of the die $\Delta = \Delta D/2$ after an intermediate service time $N = 0.40{\cdot}10^6$ strokes (as N/Δ) corresponding approximately to the time between two consecutive prophylactic sharpening used in the exploitation of blanking dies [11, 15]. The side wear was measured using the measuring machine STRATO 9-166 in fixed environmental conditions (constant room temperature of 20±2°C and relative humidity of 50...60%) as an average of five measurements. Hardmetal grade C13 (WC–13Co) was used as a primary standard tool material (after $N = 0.5{\cdot}10^5$ strokes).

Position of die	Die material grade	Deposition/coating
1	S390	-
2	S390	TiN
3	S390	(Ti,Al)N

Table 2. Composition of a 3-position tool (die) for functional testing: the tool material grade and coating (deposition) used.

3. RESULTS AND DISCUSSIONS

3.1. Adhesive wear resistance

Fig. 3 demonstrates the wear curves "h-L" of tool steels strengthened by different PVD-coatings (compared with unstrengthened steel). The results received refer to an obvious effect of PVD strengthening. The performance (wear resistance $L_{0.3}$) of the strengthened steel exceeds that of the unstrengthened one – wear resistance $L_{0.3}$ 2800 m as against 1500 for strengthened and unstrengthened steel, respectively.

The results obtained refer to a slight but obvious superiority of a TiN coating over a (Ti,Al)N one.

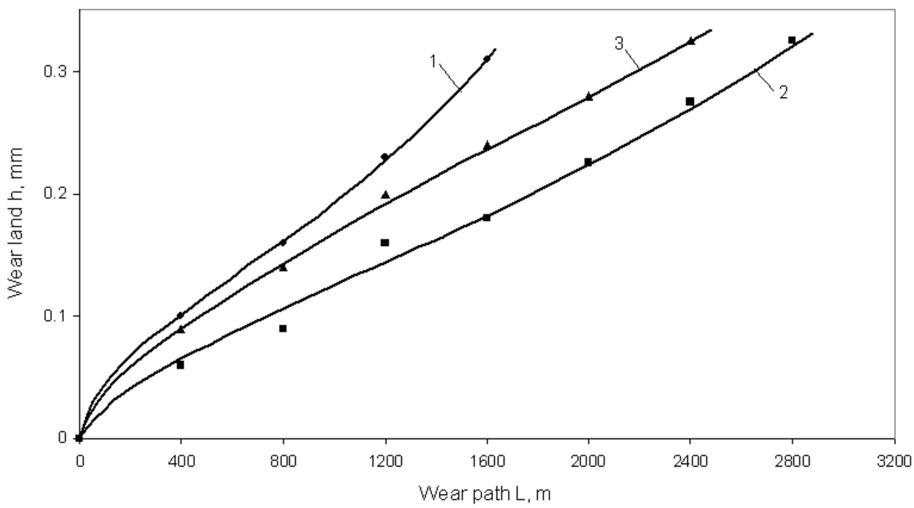

Fig. 3 Adhesive wear curves "h-L" of tool steel S390 strengthened by PVD coating and that unstrengthened

1 – unstrengthened tool; 2 – strengthened by TiN coating, 3 – strengthened by (Ti,Al)N coating.

The results presented in Figs. 3 and 4 allow us to state that the effect of strengthening by a PVD coating depends on both factors – the composition of the coating and on that of the steel (to be strengthened). Steel grade S390 with higher adhesive wear resistance (in relation to S690) ensures also a higher strengthening effect.

Surprisingly the removal of a coating (by sharpening) from the face zone of the tool (specimen) does not result in a decrease of wear resistance (increase in wear) (see Fig. 5).The flank (side) zone of the tool seems to be much more effective in strengthening of a tool than the face one. This phenomenon can be related to the differences in stress states on different faces of the cutting tool used in the testing of adhesive wear resistance [13].

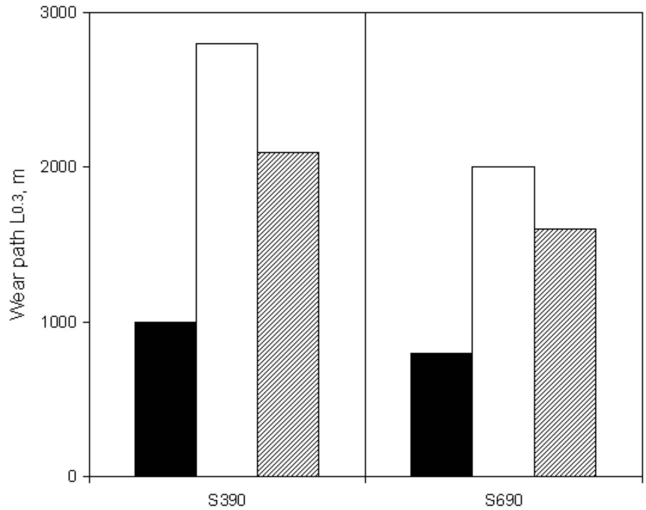

Fig. 4 Wear performance of different tool materials (steel grades S390 and S690) strengthened by different depositions: ■ - unstrengthened, □ - TiN coating; ▨ - (Ti,Al)N coating

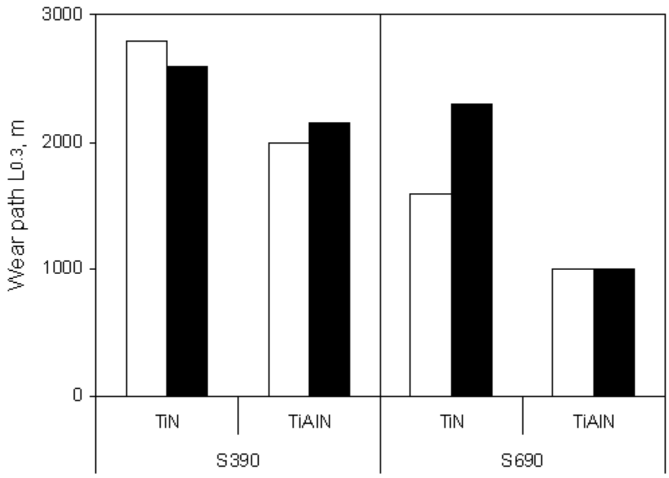

Fig. 5 Dependence of the wear performance $L_{0.3}$ of the tool (specimen) on the steel grade to be deposited (S390 , S690) and on the deposited PVD coating (TiN, (Ti,Al)N)

□ **-** all sides (flanks, faces) of the tool/specimen are strengthened by coating

■ **-** the face zone of the tool is sharpened (coating is removed by grinding)

3.2. Strength of tool steels deposited by PVD coatings

The results of strength trials (transverse rupture strength of steel S390) are presented in the form of Weibull plots in Fig. 6 (failure probability curves).

The results obtained show that strengthening of tool steel by PVD coatings (TiN) results in a slight decrease of strength. It is interesting to note that the decrease in strength is accompanied by an increase in the scatter of strength data. It should be emphasized that high performance and reliability of an alloy depends on both – the mean inert strength and its fracture resistance stability (scatter of failure data). A high scatter in strength refers to increased fragility and inclination of the alloy to untimely failure.

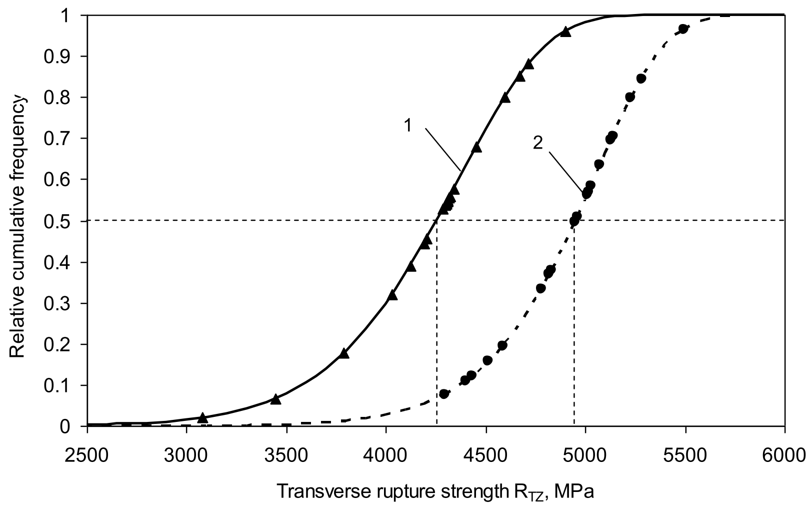

Fig. 6 Distribution curves (Weibull plots) of the transverse rupture strength R_{TZ}

1 – tool strengthened by the TiN coating; 2 – unstrengthened tool

3.3. Blanking performance

The results of functional tests – blanking of sheet metals by a three position die reinforced with tools (to be investigated) are presented in Fig. 7 as wear contours ΔD – H (side wear ΔD depending on the depth H from the cutting edge of a tool).

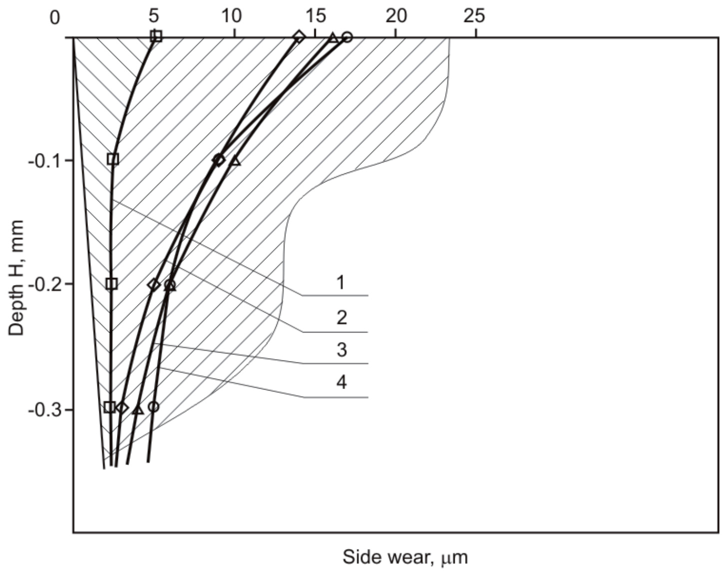

Fig. 7 Wear contours of blanking tools (their cutting edges) after blanking of $4\cdot10^5$ strokes. H – depth of the groove in the die. 1 – hardmetal C13 (WC–13Co, $5\cdot10^5$ strokes), 2 – unstrengthened tool steel, 3 – tool steel strengthened with a (Ti,Al)N coating, 4 - tool steel strengthened with a TiN coating

Fig. 7 refers to an independence of blanking performance of strengthening by a thin PVD coating. In other words, no advantages of tools strengthened by coating over those unstrengthened were revealed. Such a result is different from the influence of PVD coatings on adhesive wear performance – obvious effect of PVD strengthening on adhesive wear resistance was revealed (see Fig. 3). It is also in contradiction with the results of hardmetals performance in blanking and adhesive wear conditions. These results [11] demonstrated a good correlation between blanking performance of cemented carbides (resistance to the side wear limiting the lifetime of blanking tool) and their adhesive wear resistance.

Difference in the influence of PVD coatings on adhesive wear and blanking performance can be explained by differences in the working conditions – blanking performance was tested in cyclic fatigue while adhesive wear in constant loading conditions. In terms of practical applications thin PVD coatings (TiN, (Ti,Al)N) seem not to be effective in the strengthening of blanking tools made from tool steels and working in cyclic loading wear conditions.

CONCLUSIONS

1. The performance of adhesive wear resistance and durability in the blanking of sheet metals of some metalforming tool materials strengthened by PVD coatings was investigated. The effect of the coating on adhesive wear resistance and blanking performance was revealed.

2. It was shown that the performance in adhesive wear resistance depends on both, the composition (properties) of the PVD coating and on that of the tool material to be deposited.

3. Strengthening of tool steels by TiN and (Ti,Al)N coatings does not result in improvement of their blanking performance. No correlation between the durability in blanking and adhesive wear resistance was revealed. It can be explained by differences in testing conditions (the character of loading).

4. The PVD coating ensuring enhance adhesive wear resistance of a tool steel induces a slight decrease in strength and an increase in the scatter of strength data.

ACKNOWLEDGEMENTS

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PAPER VI

Kübarsepp, J., Klaasen, H., Tšinjan, A., Roosaar, T., Annuka, H., Wear performance of WC- and TiC-based ceramic-metallic composites, Proceedings of the International Conference BALTTRIB'2011, 2011, 150-155.

WEAR PERFORMANCE OF WC- AND TIC-BASED CERAMIC-METALLIC COMPOSITES

J.Kübarsepp, H.Klaasen, A.Tsinjan, T.Roosaar, H.Annuka

Department of Materials Engineering, Tallinn University of Technology, Estonia

Abstract: The study focuses on wear performance and failure mechanism of carbide composites, in particular alloys designed for metalforming: WC-based hardmetals and TiC-based cermets. Wear tests including adhesive wear, abrasive wear, sliding wear and wear of blanking tools were performed. The results were compared and related to the mechanical macroproperties and microstructure studied by XRD. Relationships between actual tool wear during blanking and used tool material behavior in different wear conditions were revealed.

Keywords: wear performance; cermet; hardmetal

1. INTRODUCTION

Ceramic-metallic composites − WC-based hardmetals and TiC-based cermets − are the most widely used as tool materials in machining and forming operations, as well as materials for wear components because of their excellent hardness-ductility combination. Such materials combine the high hardness of covalent refractory compounds (WC, TiC, etc.) with the toughness and plasticity of the metallic binder (usually Co, Ni, Fe). Due to high content of carbides, carbonitrides, borides etc. these materials are related to so-called "structurally brittle" materials group and are widely used P/M materials for wear applications. However, there is no complete understanding of behavior of carbide/carbonitride composites with heterogeneous structure in various wear conditions because of significant differences in wear mechanism. As an example, wear of most metal forming tools is usually classified as sliding wear based on their mechanical function. Almost all wear mechanisms could occur during sliding wear.

The main goal of this work was to investigate the wear behavior of some TiC-based cermets (prospective as tool materials in metal plastic forming) in different wear conditions: abrasive, adhesive and sliding wear and also tool wear in the blanking of sheet metals. The WC-Co hardmetals were used as reference materials. The following objectives were set in this study:

- to find out differences in the wear behavior of TiC and WC-based ceramic-metallic composites in the conditions of abrasive, sliding and adhesive wear,
- to find out relationships between tool wear in blanking and tool material properties in different wear conditions.

2. MATERIALS AND EXPERIMENTAL DETAILS

The current study focuses on the tungsten and titanium-carbide based composites prospective for metalforming: carbide fraction 74-85 vol%, properties: HRA≥86,5 (HV≥1100), transverse rupture strength $R_{TZ} \geq 1700$ MPa (Table 1). All hardmetals and TiC-based cermets were produced through ordinary P/M technology. Some low binder fraction grades (TiC-based cermets T80/14 and T75/14) were sintered by the sinter/HIP technique under gas compression of 50 bar at the sintering temperature.

Adhesive wear tests were performed by turning (facing) mild steel (HV> 150 ... 160) at low speed (v < 12 m/min) in the conditions of prevalence of adhesion [1]. Abrasive wear tests were performed by help of the rubber-rimmed rotary wheel machine (modified ASTM G65-94 method [2]) utilizing quartz sand with particle size of 0.1 – 0.2 mm as abrasive. Velocity of the wheel with diameter of 80 mm was 0.24 m/s, wear distance L = 144 m, loading F = 3 N and testing time 10 minutes. Sliding wear tests were performed in accordance with the ASTM standard B611-85 [3] without abrasive at the loading F = 40N and wear distance L = 4000 m.

Table 1. Structural characteristics and properties (hardness HV, transverse rupture strength R_{TZ}, modulus of elasticity E, proof stress in compression $R_{CO.1}$) of carbide composites.

Grade	Carbide, content, vol %	Binder; composition, structure	HV	R_{TZ}, GPa	E, GPa	$R_{CO.1}$, GPa	Used in experiments			
							Abrasive wear	Adhesive wear	Sliding wear	Blanking wear
H10	WC, 83.5	Co (W)	1350	2.3	610	2.9	x	x		
H13	WC, 79.9	Co (W)	1300	2.8	590	2.9	x	x		x
H15	WC, 76.0	Co (W)	1150	2.9	560	2.5	x	x		
H20	WC, 69.0	Co (W)	1000	3.1	510	2.0	x	x		
T80/14 (sinterhipped)	TiC, 86.5	14Ni-steel austenite-bainite	1450	1.5/2.1	420	3.0/3.2	x	x	x	
T75/14 (sinterhipped)	TiC, 83.0	14Ni-steel, austenite-bainite	1350	1.8/2.4	410	2.8/2.9	x	x	x	x
T70/14	TiC, 79.0	14Ni-steel, austenite-bainite	1250	2.3	400	2.3	x	x	x	x
T60/14	TiC, 74.0	14Ni-steel, austenite-bainite	1050	2.4	380	1.9	x	x	x	
TN30	TiC, 81	NiMo (2:1)	1380	1.7	380	2.3	x	x	x	
TN40	TiC, 74	NiMo (2:1)	1260	1.9	360	2.0	x	x	x	
TN50	TiC, 65	NiMo (2:1)	1000	2.1	340	1.7	x	x	x	

The procedure of the durability functional test – wear tests in blanking – resembled that in industrial service, i.e. blanking of grooves into electrotechnical sheet steel of low hardness (~150 HV) and thickness of 0.5 mm [4]. The wear resistance was evaluated by the measurement of the side wear of the die (Δ after an intermediate service time $N = 0.5 \cdot 10^6$ strokes). The blanking performance was evaluated as increase in side wear after an intermediate service time $N = 0.5 \cdot 10^6$ as N/Δ (lifetime in strokes per 1 mm of side wear).

Microstructural aspects of surface failure of carbide composites were performed utilizing XRD investigations performed on the diffractometer Bruker D5005. Changes of fine intensities of X-ray reflections from composites carbide phase (line peaks) and their broadening were determined in the XRD studies [5].

3. RESULTS AND DISCUSSION

3.1. Adhesive wear

The results refer to an obvious dependence of the alloys wear performance on their composition (see Fig. 1). At equal hardness as well as at equal carbide content adhesive wear performance of different composites differ markedly. WC-base hardmetals and TiC-based cermets cemented with Fe-Ni alloy (Ni-steel) show a remarkable superiority over ordinary TiC-based cermets cemented with Ni-Mo alloy.

In Fig. 2 the wear performance of composites is opposed to their proof stress featuring material resistance to plastic strain and to shear failure. The relationships refer to an obvious dependence of adhesive wear on proof stress – the increase in proof stress improves monotonously the wear resistance.

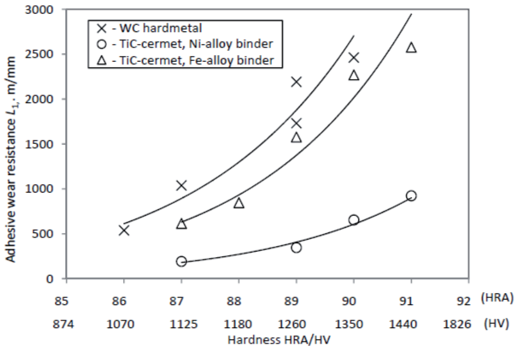

Fig.1. Adhesive wear resistance of carbide composites vs hardness

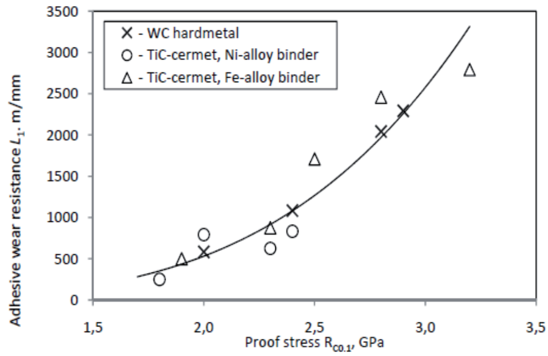

Fig.2. Adhesive wear resistance of carbide composites vs proof stress

As stated, the plastic strain of carbide composites takes place preferably in its metallic binder [6, etc]. The XRD measurements performed in the present study on the worn surfaces of composites revealed alterations in their diffractograms – a decrease in the intensities and an increase in the broadness of the reflection lines of their carbide phases (see Fig. 3). These alterations refer to changes in the fine structure of the carbide phase induced by their plastic strain taking place during loading [1].

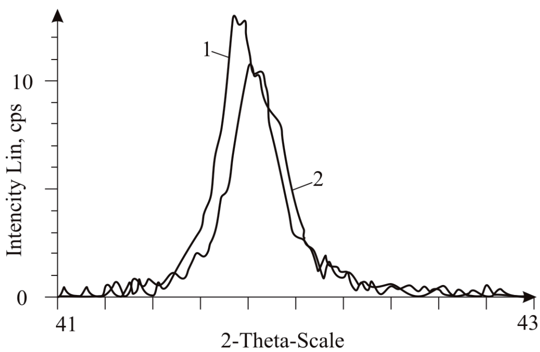

Fig.3. XRD diffraction patterns of the carbide phase [line 200] of the TiC-based cermet: 1 – before testing; 2 – after adhesive wear testing

3.2. Abrasive wear

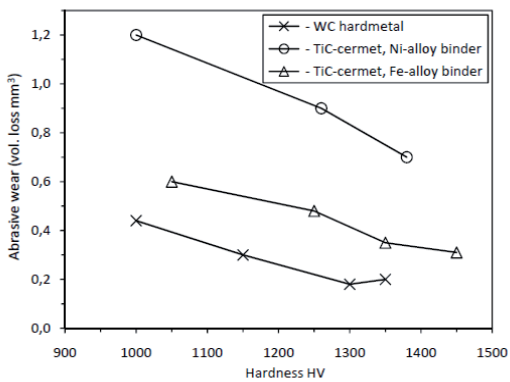

Fig.4. Abrasive wear of carbide composites vs hardness

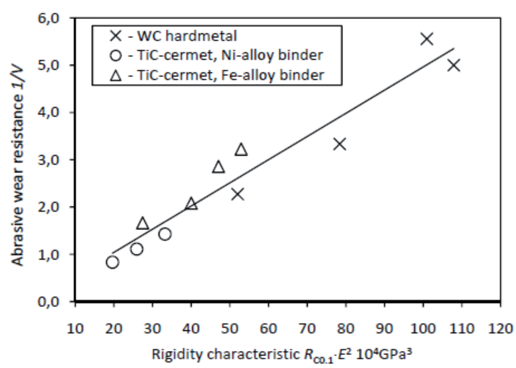

Fig.5. Abrasive wear performance 1/V vs. rigidity characteristic $R_{C0.1}{\cdot}E^2$ of carbide composites

The results obtained (see Fig.4) refer to an obvious dependence of the wear performance on the composition of alloy. At an equal hardness (and also at equal carbide fraction) tungsten carbide-based composites demonstrate an obvious superiority over TiC-based cermets.

Results confirm as also in the case of adhesive wear (Fig.1) an inconclusive influence of hardness on the wear performance of composites of different composition of carbide and metal phase. Results presented in Fig. 5 confirm that rigidity characteristic $R_{c.0.1} \cdot E^2$ (proof stress in compression $R_{c.0.1}$ times modulus of elasticity E) of carbide composites is better tool for prognostication of abrasive wear resistance of composites of different composition.

The XRD measurements performed in the present study on the worn surfaces of carbide composition revealed alterations in their diffractograms – decrease in the intensities and an increased broadness of the reflection lines of their carbide phase (see Fig. 6). These alterations refer to changes in the fine structure of the carbide phase induced by their local plastic strain (dispersity of micrograins and density of dislocation network).

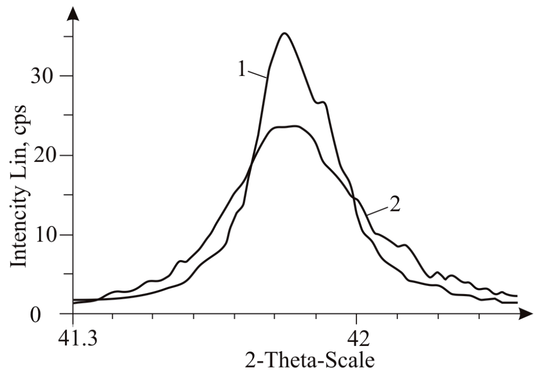

Fig.6. XRD diffraction patterns of TiC-based cermet carbide phase [line 200]: 1 – before testing; 2 – after abrasive wear testing

3.3. Sliding wear

In essence, the results of sliding wear tests represent those of abrasive and adhesive wear ones. WC-based hardmetals have obvious superiority over tungsten-free cermets and cermet with steel binder (Fe-Ni) over composite with nickel alloy (Ni-Mo) binder (see Fig. 7). In contrast to adhesive wear and abrasive wear the sliding wear demonstrated a relatively low sensitivity in terms of carbide content.

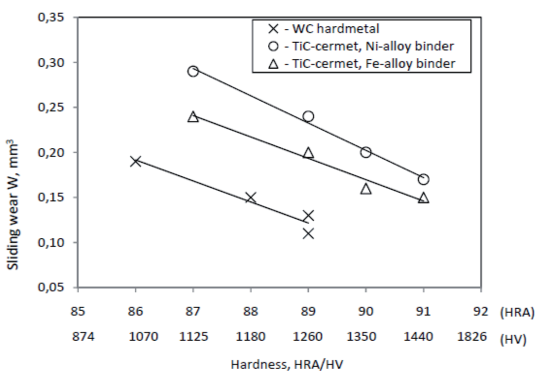

Fig. 7. Sliding wear vs hardness of carbide composites

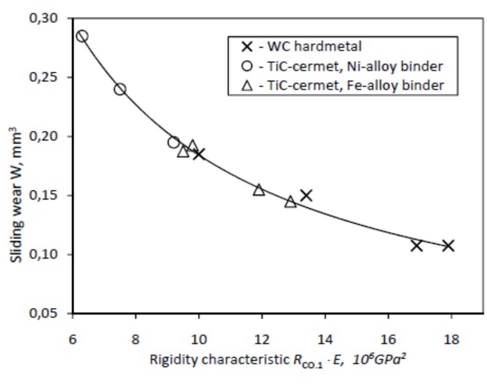

Fig.8. Sliding wear vs rigidity characteristic $R_{c.0.1} \cdot E$ of carbide composites

Fig. 8 demonstrate the dependence of the sliding wear of the test materials on the proof stress $R_{c.0.1}$ and modulus of elasticity E as a combined stiffness characteristic $R_{c.0.1} \cdot E$. In general, the relationships repeat those revealed for the adhesive wear – the uncertainty of hardness and the definitive relevance of proof stress. In contrast to adhesive wear sliding wear demonstrated a more definitive dependence on the modulus of elasticity E. Results also confirm a comparatively low structure sensitivity of carbide composites in sliding wear conditions.

3.4. Wear of blanking tool

Results of functional wear tests are shown in Fig. 9.

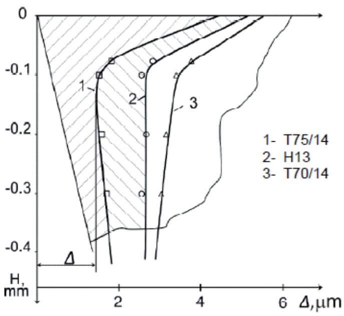

Fig.9. Wear contours of carbide tool (die) edges – side wear after blanking of $0.5 \cdot 10^6$ strokes. *H* – depth of groove measured from cutting edge, *Δ*− side wear.

Cutting edges of blanking die became blunt as a result of uniform wear. Wear contours demonstrate the obvious superiority of the TiC-based cermet T75/14 over hardmetal H13.

3.5. Correlation between different wear conditions

In Fig. 10 the blanking performance of tested composites is opposed to their durability characteristics in different wear conditions – in abrasive wear, adhesive wear, sliding wear. Results confirm the considerations and conditions presented above. They refer to the existence of good correlations between blanking performance of composites and their adhesive wear resistance. High blanking performance is achieved if it posses both high adhesive wear resistance and also low fatigue sensitivity [7].

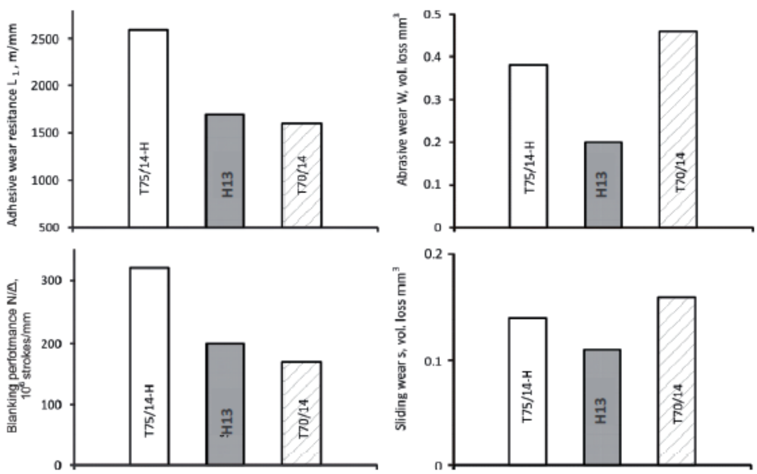

Fig.10. Blanking performance N/Δ of carbide composites and their response as inserts in adhesive, abrasive and sliding wear conditions

On the basis of results, presented in Fig. 10, it can be concluded that between composites blanking performance and their resistance to abrasive and sliding wear there does not exist any definite correlation. The higher blanking performance of TiC-based cermet – compared to WC-based hardmetal, results from its higher resistance to adhesive wear and also fatigue damage (lower fatigue sensitivity).

As stated above the abrasive and sliding wear resistance of a TiC-based cermet compare unfavorably with WC-based hardmetal. These results refer to an existence of a correlation between performances of composites exploited (tested) in different wear conditions (abrasive, erosive, sliding wear).

4. CONCLUSIONS

1. Wear performance in different wear conditions of the TiC-based cermets and the WC-based hardmetals were compared. In abrasive and sliding wear conditions, the hardmetals showed superiority over the cermets. In blanking and adhesive wear conditions TiC-based cermets demonstrated the same level of resistance to wear as hardmetals but certain advanced cermets compare favorably with the hardmetals.
2. Wear performance predicted on the basis of hardness may lead to pronounced mistakes when carbide composites of different composition are considered.

3. The results of the comparison of tool wear in blanking and tool material (TiC-based cermets and hardmetals) performance in different wear conditions and their wear mechanisms revealed a good correlation between the blanking performance and adhesive wear resistance.

4. Novel characteristics – more reliable than hardness – for prognostication of wear performance have been developed. They feature stiffness of a material (composite) – its resistance to elastic strain (estimated by the modulus of elasticity) and plastic strain (estimated by proof stress).

5. The fact that certain advanced TiC-based cermets outperformed hardmetals in the wear condition with prevalence of adhesion makes them favorable tool materials in blanking and in other working conditions with prevalence of adhesion.

Acknowledgements

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Author for contacts:
Jakob Kübarsepp.
Department of Materials Engineering, Tallinn University of Technology, Ehitajate tee 5, 19086, Tallinn, Estonia.
Phone: +372 6203354; Fax: +372 6202020; E-mail: jakob.kubarsepp@ttu.ee

CURRICULUM VITAE (CV)

Name	Aleksei Tsinjan	
Date of birth and place	07.03.1981, Tallinn, Harjumaa, Estonia	
Citizenship	Estonia	
Address	Pune tee 18-8, 12015, Tallinn, Estonia	
Phone	+3725283810	
E-mail	aleksei.tsinjan@ttu.ee	
Education	2003-2005	Tallinn University of Technology, faculty of transportation engineering. MSc
	1999-2003	Tallinn University of Technology, BSc
	1987-1999	Tallinn Lasnamäe Gymnasium
Professional Employment	2005 - …	AS Norma - Product Engineer
	2003-2005	Ecopress Group OÜ – Design Engineer
Field of Research	Natural Sciences and Engineering, Process Technology and Materials Science	
Language competence	Russian – native language	
	Estonian – high level	
	English – high level	

Elulookirjeldus

Nimi	Aleksei Tsinjan	
Sünniaeg ja -koht	07.03.1981, Tallinn, Harjumaa	
Kodakondsus	Eesti	
Aadress	Pune tee 18-8, 12015, Tallinn	
Telefon	+3725283810	
E-post	aleksei.tsinjan@ttu.ee	
Hariduskäik	2003-2005	Tallinna Tehnikaülikool, transporditehnika õpesuund, Tehnikateaduste magister
	1999-2003	Tallinna Tehnikaülikool, transporditehnika õpesuund, Tehnikateaduste bakalaureus,
	1987-1999	Tallinna Lasnamäe Gümnaasium
Teenistuskäik	2005 - …	AS Norma - Tooteinsener
	2003-2005	Ecopress Group OÜ – Tooteinsener
Teadustöö põhisuunad	Loodusteadused ja tehnika, Protsessitehnoloogia ja materjaliteadus	
Keeleoskus	Vene – emakeel	
	Eesti keel – kõrgtase	
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