THESIS ON MECHANICAL ENGINEERING E86

Wear of PVD Coatings on Fineblanking Punches

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TUT PRESS

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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 E86

PVD pinnete kulumine silelõikestantsi templitel

LIINA LIND

TTÜ KIRJASTUS

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LIST OF PUBLICATIONS

The present doctoral dissertation is based on the following peer reviewed publications, referred to in the text by Roman numerals **I-III**:

Paper I **Lind, L**., Peetsalu, P., Põdra, P., Adoberg, E., Veinthal, R., Kulu, P. (2010). Description of punch wear mechanism during fine blanking process. *Proceedings of 7th International Conference of DAAAM Baltic Industrial Engineering*, 504 - 509.

Paper II **Lind**, **L**., Adoberg, E., Aarik, L., Kulu, P., Veinthal, R., Alsayed, A.A.I. (2012). Tribological properties of PVD coatings with lubricating films. *Estonian Journal of Engineering*, 18(3), 193 - 201.

Paper III **Lind**, **L.**, Peetsalu, P. Sergejev, F. Wear of different PVD coatings at industrial fine-blanking field tests. *Materials Science (Medžiagotyra)*, (accepted).

Copies of these articles are included in the Appendices.

Other publications related to the thesis, referred to in the text by letters **A** and **B**:

Paper A Peetsalu, P., Saarna, M., Adoberg, E., Kulper, E., **Lind, L.**, Kulu, P. (2010). Evaluation of punch wear resistance during industrial test. *Acta Metallurgica Slovaca Conference*, 105-110.

Authors' contribution: involvement into the planning and testing; surface roughness measurements; analysis of the results; minor part of writing.

Paper B Adoberg, E., Podgurski, V., Peetsalu, P., **Lind, L.**, Mikli, V., Hvizdos, P., Kulu, P. (2012). The effect of surface pre-treatment and coating post-treatment to the properties of TiN coatings. *Estonian Journal of Engineering*, 18(3), 185-192.

Authors' contribution: involvement into the planning and testing.

INTRODUCTION

Motivation for the research

Estonia will not continue to be an inexpensive production country. Therefore it is essential to promote knowledge-based industry where research and development are the foundation of production. Recent government support to materials science projects combined with continuous collaboration between Estonian tool manufacturers and Tallinn University of Technology has promoted efforts for uniting scientific research with industrial applications. Driven by this collaboration, our research group has been provided a unique possibility to apply our Physical Vapour Deposited (PVD) coatings at the industrial scale in fineblanking applications and to acquire feedback from the coatings performance.

Fineblanking (also fine-blanking, fine blanking or precision blanking) is a severe sheet metal forming process (Bay *et al.* 2008) where the goal is to achieve smooth-sheared edges over the entire workpiece thickness in one single operation (Chen *et al.* 2002). As a common practice, the clearance between the punch and the die is set to 0.5-1 % of a workpiece thickness (Lange *et al.* 1997). Striving towards a 100 % sheared surface, the tools are operated at the extreme limit with minimal punch-die clearance, resulting in very limited life-time of cutting instruments due to high contact pressures. The result is a constant demand for new tools. The complex shape, high precision requirements and high hardness together with the PVD coating process of the tools make their production time-consuming and expensive. Increased punch wear resistance would result in financial savings.

Fineblanking is a rather confined area where the know-how is commonly transmitted inside the community. Therefore, also the knowledge shared through the scientific publications is limited. A certain amount of the know-how is always kept inside the companies. As a result, practitioners often apply fineblanking based on their everyday experience (Chan *et al.* 2004). From the research perspective, the objective was to improve the fineblanking tool life-time through a systematic analysis. A motivation was to find an experimental test that could be used to predict the performance of different PVD coatings at fineblanking application and to find the coating properties that are important in determining the wear resistance of coatings at industrial applications. It is known that tribological testing of coatings in a laboratory situation gives us certain numerical properties that could be used to rank the coatings based on their test performance. However, it is not so well known which properties have a leading role in industrial fineblanking applications. The question is if it is the punch preparation (e.g. surface topography), mechanical properties of the hard coating or something else.

Scientific novelty

In the scope of the present thesis an *industrial field testing method was developed* and applied to evaluate the wear resistance of different coatings at fineblanking punches. In the literature several studies report fineblanking tests used to assess the influence of different variables (e.g. lubricant, substrate, clearance) on the tool life-time. However, methods for testing different coatings and the test results concerning the performance of different coatings at the industrial fineblanking are not described in this extent in the studies published.

PVD coating field tests are essential to understand coating wear behavior in its application. *Coating wear mechanism of ground punches is described and illustrated with schemes and SEM images* in Paper I. Microblasted punches studied in Paper III exhibited coating detachment in discrete areas (a wear mechanism also presented by Gerth (Gerth *et al.* in 2009)). However, in the present thesis *supplementary information regarding the mechanism and reasons for coating detachment is provided*.

Several studies have reported that from the wear resistance perspective, coatings applied in fineblanking application are expected to have low modulus of elasticity (E) and high hardness (H). Our industrial field tests confirmed the findings of other researchers reporting that wear resistance is related to the H/E ratio (also known as elastic strain to failure). A connection was found that *coatings with higher H/E ratio had better wear resistance at the fineblanking field tests*.

Approbation

Scientific results presented in the thesis have been previously presented at the following international conferences:

1. The 14th International Symposium on Metallography, 28-30 April, Starà Lesnà, Slovak Republic (2010)
2. The 7th International DAAAM Baltic Conference "Industrial Engineering", 22-24 April, Tallinn, Estonia (2010)
3. The 21st International Baltic Conference BaltMatTrib, 18-19 October, Tallinn, Estonia (2012)
4. The 5th World Tribology Congress, September 8-13, Torino, Italy (2013)
5. The 9th International DAAAM Baltic Conference "Industrial Engineering", 24-26 April, Tallinn, Estonia (2014)

ABBREVIATIONS AND SYMBOLS

Abbreviations:

ALD	– Atomic Layer Deposition
ASB	– Adiabatic Shear Band
CoF	– Coefficient of Friction
CVD	– Chemical Vapour Deposition
DLC	– Diamond-Like Carbon
EDM	– Electrical Discharge Machining
EDX	– Energy-Dispersive X-ray spectroscopy
FB	– Fineblanking (also fine-blanking, fine blanking and precision blanking)
FE	– Finite Element
FEM	– Finite Element Method
GR-H-punch	– industrial fineblanking punch with chamfer at the cutting edge prepared using H-type grinding as finishing treatment
GR-M-punch	– industrial fineblanking punch with chamfer at the cutting edge prepared using M-type grinding as finishing treatment
HM	– Hard metal
HSS	– High Speed Steel
MB-punch	– industrial sharp fineblanking punch prepared using micro-blasting as finishing treatment
nACo	– commercial name for nanocomposite PLATIT hard coating nACo® = (nc-AlTiN)/(a-Si_3N_4)
nACRo	– commercial name for nanocomposite PLATIT hard coating nACRo® = (nc-AlCrN)/(a-Si_3N_4)
PM	– Powder Metallurgy
PVD	– Physical Vapour Deposition
R(1-6)	– row number in the fineblanking tool assembly
SEM	– Scanning Electron Microscopy
STDEV	– Standard deviation
TiCN-MP	– MultiPurpose TiCN coating from Platit
TUT	– Tallinn University of Technology

Symbols:

E	– Modulus of elasticity (also Young's modulus, indentation modulus)
F	– Force
H	– Hardness of the coating (also nanohardness)
H/*E*	– Hardness and modulus of elasticity ratio
Ra	– Average surface roughness
Rz	– Mean roughness depth

1 THEORETICAL BACKGROUND

1.1 Fineblanking process description

Fineblanking (FB) is a sheet metal working process for producing metal components with smooth-sheared edges and high degree of dimensional accuracy over the entire workpiece thickness in one single operation (Chen *et al.* 2002, Feintool Edition 2012, Golovashchenko 2006, Li *et al.* 2003). High quality details are produced in virtue of using the combination of three forces: F_1 (cutting force), F_2 (vee-ring force) and F_3 (counter force). In conventional blanking, parts are cut only by using the F_1 (Fig. 1.1) (Feintool Edition 2012, Thipprakmas 2011). Additionally, smaller punch–die clearance ~0.5 % of the blanking material thickness is used as compared with conventional blanking where the clearance is ~10 %. As a result of the described FB setup, high hydrostatic pressure is accomplished and severe plastic deformation is localized in a narrow shear band near cutting clearance (Xie *et al.* 2006, Chen *et al.* 2003), also known as adiabatic shear band (ASB) (Gotoh *et al.* 2001, Neugebauer *et al.* 2012). In the described conditions, metals can undergo much higher plastic deformation without fracture, resulting in a very clean sheared surface (Golovashchenko 2006, Chen *et al.* 2003). Near the punch tip, the damage work density starts increasing quickly when the punch penetration is greater than 84 % of the thickness of the workpiece. When the punch penetrates 90 % into the material thickness, macrocracks are initiated from the tip of the tools (Chen *et al.* 2002, Chen *et al.* 2004).

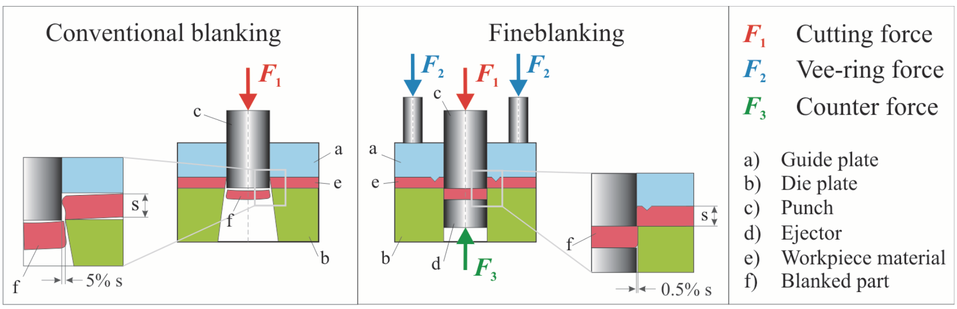

Figure 1.1 Forces and precision in conventional and fineblanking.

V-ring is very important in increasing the edge quality of the blanked part (Kwak *et al.* 2003, Thipprakmas 2009, Kim *et al.* 2013a, Ding *et al.* 2013). The application of the V-ring indenter increases the compressive stress inside the sheet metal before the cutting phase, and significantly suppresses the rotation of the material flow during the cutting phase, thereby further increasing the hydrostatic compressive stress and preventing crack formation (Thipprakmas 2009).

Combination of contact pressure and relative velocity leads to a state of boundary lubrication or solid-solid contact (Klocke *et al.* 2001b, Straffelini *et al.*

2010). However, if not lubricated, coated punches fail to give acceptable performance regardless of the coating and substrate used, heavy increase in the cutting force and tool failure would take place (Podgornik *et al.* 2011).

Contact pressures around 3000 MPa can be expected in some areas of the contact zone. In the front face corner of the blanking punch, contact pressures are even reported to rise to the level of 3500 MPa (Klocke *et al.* 2001b). The strain concentration is roughly inversely proportional to the radius of the tools, i.e. the smaller the radius of the tools, the larger the strain concentration (Chen *et al.* 2002). Furthermore, the effective strains are highly localized at the punch tip and the die corner (Leung *et al.* 2004), increasing the possibility of cracks and fractures occurring in the area. Temperatures during FB are reported to be around 400 °C (Klocke *et al.* 2001b).

In brief, there are many factors influencing the life-time of tools, the process of shearing and the condition of the sheared surface (Shim *et al.* 2004, Leskovšek *et al.* 1997, Monteil *et al.* 2008, Lauwers *et al.* 2005): the punch, the die, the speed of punching, the lubrication, the clearance between the punch and the die, and the properties of the workpiece material.

1.1.1 Fineblanked product quality defects and defects of punches

The clearance and its uniformity along the peripheral edge are the most important factors affecting the quality of final products (Lee *et al.* 2005, Hong 2011, Shuqin *et al.* 2002, Tekiner *et al.* 2006). Clearance should be higher for better plastic material and smaller for the low (Hong 2011). With increased clearance, the shear band of the material is widely spread, leading to earlier tearing and also increase in the width and depth of the die-roll (Kwak *et al.* 2002, Kim *et al.* 2013b, Kim *et al.* 2013c) and formation of burr (Hambli 2001, Straffelini *et al.* 2010). With a decrease of the clearance, the depth of the fracture zone is decreased and the depth of the shear zone is increased (Kwak *et al.* 2002, Wang *et al.* 2012). However, too small clearance causes bulging (Kim *et al.* 2013b, Kim *et al.* 2013c) and from conventional blanking it is known that it increases the blanking load (Maiti *et al.* 2000).

The following characteristic zones and defects can be distinguished on the products (Fig. 1.2):

- The *roll over zone* (i.e. die-roll). This is the part of the edge drawn into the sheet by the punch. Roll-over does not significantly depend on the friction coefficient (Klocke *et al.* 2001a).
- The *sheared zone*. This zone is formed by the punch before the onset of a fracture. Generally, the surface of the sheared zone is rather smooth (Chen *et al.* 2004). A shear zone, i.e. a clean-cut zone, is the objective and it is expected to be equal to the workpiece material thickness in fineblanking.
- Occasionally *tearing* (also tear-off or fracture zone) with a characteristic rough zone can form, however it could be prevented by good ductility of the workpiece material and good lubrication of the process (Chen *et al.* 2004).

Tearing is affected by the clearance, punch geometry, cutting speed and material microstructure.

- *Burr* is formed because of the specific location of the fracture initiation (Brokken *et al.* 2000). For example, at the punch wear, the fracture initation starts later because of changed die clearance.
- *Scars* are characteristic for complex-shaped products and at small radii. Typical location of scarring is in the middle of material thickness (Fig. 1.2); the cause may be associated with insufficient lubrication or too high cutting speed (Kwak *et al.* 2002).

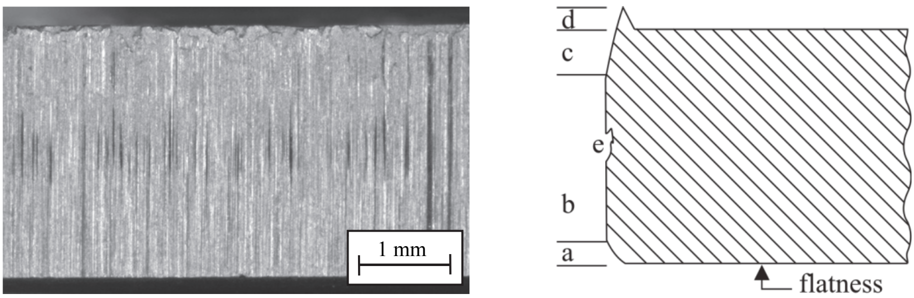

Figure 1.2 Photograph of a clean-cut fineblanking product together with a scheme showing characteristic zones and possible defects of the product: a – roll over, b – shear, c – tearing, d – burr, e – scar.

The described defects on the product are the basis for the operator to decide when the tool needs maintenance. However, all of the above described defects of products are caused by the defects on the tools. Defects on the punches are known as wear, chipping and fracture. A fracture may be caused by improper tool adjustment or fatigue wear and is the most severe failure since grinding or cutting off the broken section may not be possible and the punch needs to be replaced.Wear of the punches causes the increase of the clearance and an extensive wear leads to chipping of the punch in small fragments.

1.2 Main research directions in the field of fineblanking

During fineblanking the tool/workpiece interface is exposed to high contact pressure combined with high temperature and complicated access of oil into the interface where the punch stem is in contact with the formed virgin metal surface (Olsson *et al.* 2002). Chemically active additives could be used in lubricants to form a protective boundary film; however, they are often hazardous to the environment and humans, therefore greater attention is paid to ceramic coatings for tools together with reduced use of oil and developing biodegradable, additive-free lubricants for metal forming and cutting (Bay *et al.* 2010, Klocke *et al.* 2005, Lugscheider *et al.* 2004, Klocke *et al.* 2001b, Klocke *et al.* 2006, Hogmark *et al.* 2000, Holmberg *et al.* 2007).

Many different FEM simulations have been created to predict either material flow within the sheet metal (Thipprakmas *et al.* 2007b), V-ring effect (Kwak *et al.* 2003, Thipprakmas 2009, Thipprakmas 2010), clearance influence (Fang *et al.* 2002, Kwak *et al.* 2002), defects formation on the product (Yu *et al.* 2007), die radius effect (Thipprakmas *et al.* 2008) or die wear during fine blanking (Yin *et al.* 2012). Results obtained with FEM are in agreement with experimental case studies, indicating that simulations may be helpful for predicting the life-time of tools or designing and choosing the tool parameters, thus enabling reduced need for expensive trials (Yin *et al.* 2012, Chan *et al.* 2004, Chen *et al.* 2002, Hambli 2001, Thipprakmas *et al.* 2007a, Thipprakmas *et al.* 2007b). However, demanding technological requirements, for example, a complicated contour product shape remarkably complicates FE-modelling (Thipprakmas *et al.* 2008).

Generally, fineblanking research is finance-driven and the goal is to reduce the costs by extending the life-time of tools and relieving design problems. Re-using the tools could also be one way to cut costs. Bouzakis *et al.* (Bouzakis *et al.* 2004) investigated the possibility of reconditioning cutting tools of cemented carbide by the following procedure: electrochemical de-coating followed by micro-blasting and PVD coating. Nevertheless the results are not very promising since reconditioned tools were found to have deteriorated mechanical properties of the substrate and in general low wear behavior.

Another steady course in FB is striving towards cost-save at the expense of direct fineblanking of high strength steels as an alternative to using post-fineblanking heat-treatment (Gram *et al.* 2011). The main challenge, again, is tool life. Gram *et al.* (Gram *et al.* 2011) propose a significant increase of workpiece strength by using blanking materials with optimized properties while maintaining the same tool life.

1.3 Advanced substrate-coating systems in fineblanking and wear resistant coating trends

Good results in FB have been obtained by combining powder metallurgical (PM) high speed steel (HSS) with hard coatings (Bay *et al.* 2010, Straffelini *et al.* 2010, Podgornik *et al.* 2011). Substrate hardness has to be high enough to resist abrasive wear and to provide support to the hard coating (Hogmark *et al.* 2000, Klocke *et al.* 2001b, West *et al.* 2003). Feintool recommends that the tool should have high compressive strength and edge stability, i.e. hardness of at least 63 HRC (Maurer 2014). High fracture toughness enables the material to withstand crack development during cyclic loading. Wear resistance (i.e. hardness) is in strong dependence of toughness – the higher the hardness, the lower the toughness and *vice versa*. Therefore it is quite challenging to find an optimal balance between these two parameters.

Next, it is important to have a good pre-treatment before the coating process since deposition follows the surface contour and it is impossible to correct poor pre-treatment afterwards (Hogmark *et al.* 2000). Surface topography influences the friction, lubrication and final surface quality in metal forming operations

(Bay *et al.* 2010, Bobzin *et al.* 2009). Sergejev *et al.* have reported that surface roughness is the most critical parameter influencing the punch life-time (Sergejev *et al.* 2011). Furthermore, increased surface roughness facilitates the lubricant entrainment and transport, especially when liquid lubricants are applied (Bay *et al.* 2010). Oerlikon Balzers suggests that the average surface roughness *Rz* should lie within the same order of magnitude as the coating thickness. The reason is that at higher surface roughness values, there is a danger of the coating being sheared off at the roughness peaks or breaking down because of too high local surface pressures (Oerlikon Balzers, Wiklund *et al.* 1999). The pre-treatment of tools and surface topography should provide the greatest possible bond between the coating and the substrate (Podgornik *et al.* 2011, Klocke *et al.* 2005, Lugscheider *et al.* 2004, Bobzin *et al.* 2009). Podgornik *et al*. (Podgornik *et al.* 2011) state that the coated tool performance is mainly determined by the coating adhesion and substrate preparation, followed by the coating wear resistance and toughness.

Mechanical behavior of the coating has a strong influence on the tribological processes. For example, Young's modulus of the coating influences the stress developing within the coating during contact. High tensile stress causes formation of microcracks, which will coalesce and lead to coating failure. Therefore a low Young's modulus, i.e. higher ductility, is a desired property of a tribological coating accompanied with high hardness, providing high wear resistance (Klocke *et al.* 2005, Lugscheider *et al.* 2004, Bobzin *et al.* 2009, Straffelini *et al.* 2010, Leyland *et al.* 2000). However, the requirement of high coating hardness should not be prioritized since most counter surfaces expected for tribological applications of coated components are softer than 20 GPa, a value exceeded by many of today's coatings (Hogmark *et al.* 2000).

Resistance to crack development within the coating should be high (Klocke *et al.* 2001a, Bobzin *et al.* 2009). Nanostructured multilayer and superlattice coatings are developed to relieve this problem (Klocke *et al.* 2005) and obstruct dislocation glide and crack propagation (Hogmark *et al.* 2000) as well as provide a reduced Young's modulus and, at the same time, increased hardness (Nordin *et al.* 1999, Lugscheider *et al.* 2004, Hogmark *et al.* 2000). Furthermore, by the reduction of the thickness of each single layer of the coating system its wear resistance could increase incrementally (Lugscheider *et al.* 2004).

High residual stress could cause spontaneous coating delamination. A balanced compressive residual stress state seems desirable: it needs to be compressive enough in order to compensate tensile stresses arising through an external load (Klocke *et al.* 2001a, Holmberg *et al.* 2009, Hogmark *et al.* 2000). It is reported that for example, high thickness of the coating could be a starting point for a large residual stress (Sergejev *et al.* 2011, Cao *et al.* 2012). Therefore, compressive coating stresses are beneficial to the wear protection only if the coating thickness and edge radius of tools are optimized (Gerth *et al.* 2009).

Reports regarding the influence of the coefficient of friction (CoF) on the fineblanking tool wear provide contradictory data. Some publications indicate that low CoF could increase the wear resistance (Straffelini *et al.* 2010) while other sources (Sergejev *et al.* 2011, Lugscheider *et al.* 2004) point out that reduced CoF has minor influence on the wear, especially in the case of industrial applications (Sergejev *et al.* 2011). From conventional blanking it is known that increased CoF adds to the blanking load (Maiti *et al.* 2000).

Regarding specific coatings, the Balzers AlCrN is reported to give three times longer life-time than TiN or TiCN (Oerlikon Balzers, Podgornik *et al.* 2011). With the passive behavior of Chromium (Cr), high long-term oxidation protection and superior abrasive wear resistance is achieved (Lugscheider *et al.* 2004, Kalss *et al.* 2006). Aluminum (Al) increases hardness of the coating while the Ti-based coatings earn their popularity from the fact that they combine coverage of a broad "medium range" of mechanical and thermal properties with an adequate rate of deposition during the coating process and good bonding to the usual tool substrates (Klocke *et al.* 1999). The (Al,Cr)N system has a lower thermal conductivity than the (Al,Ti)N system and therefore better ability to protect the tool steel (Maurer 2014).

Top coatings combined with hard PVD base-coatings have also been studied by different research groups. For example, nanostructured CrN is used to reduce the CoF by providing a lubrication supporting the functional surface (Bobzin *et al.* 2009). Renevier *et al.* (Renevier *et al.* 2000) have been successful in using MoS_2/Titanium composite on top of a TiCN coating at fineblanking punches. Although showing the lowest friction, TiAlN + DLC coated punch results in the highest force acting on the punch at the point of steel-sheet breakthrough and during punch extraction caused by complete removal of the top DLC layer (Podgornik *et al.* 2011). Furthermore, Nyberg *et al.* (Nyberg *et al.* 2013) used sacrificial carbon overcoat on a low friction coating, where as a result CoF increased, however the overcoat proved to be beneficial in decreasing the wear in short-term sliding wear tests.

In addition, concerning post-treatment of coatings, mild microblasting on PVD films is an efficient method for inducing compressive stresses, increasing the coating hardness and toughness as well as tool life of coated hard metal tools (Klocke *et al.* 2007, Hogmark *et al.* 2000). Bouzakis *et al.* (Bouzakis *et al.* 2009a, Bouzakis *et al.* 2009b, Bouzakis *et al.* 2011a) have used microblasting to increase the coating hardness on milling tools, however the method may cause film brittleness and local substrate revelations.

1.4 Wear mechanisms related to fineblanking

It is important to know the circumstances when the coatings on the tool surfaces fail. Therefore, carrying out tests on real processes to observe which mechanisms are responsible for coating failure is particularly important (Klocke *et al.* 2005, Klocke *et al.* 1999). Wear during fineblanking is caused by sliding and may be characterized by adhesion, abrasion, transfer phenomena and also by brittle surface microcracking occurring simultaneously, as well as act upon and influence each other (Straffelini *et al.* 2010, Klocke *et al.* 2005, So *et al.* 2012). Below is a short overview of the wear mechanisms.

1.4.1 Abrasive wear

Abrasive wear occurs when a hard rough surface slides across a softer surface (Rabinowicz 1995). The two modes of abrasive wear are known as two body and three body abrasive wear (Fig. 1.3). Two body wear occurs when the grits or hard particles remove material from the opposite surface. Three body wear occurs when the particles are not constrained, and are free to roll and slide down a surface. Hard abrasive particles (e.g. detached droplets from the PVD film) could cause three body abrasive wear in the fineblanking operation.

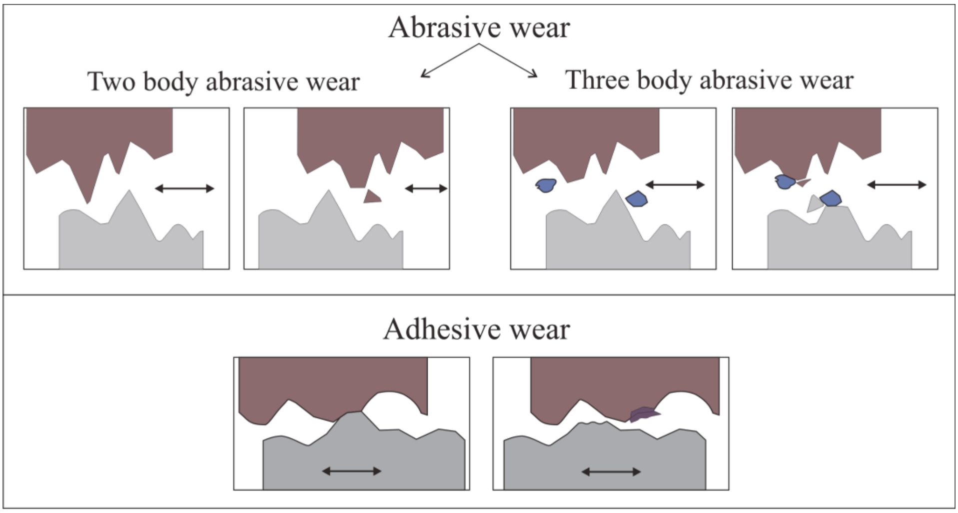

Figure 1.3 Abrasive and adhesive wear mechanisms.

1.4.2 Adhesive wear

Adhesive wear mechanism is based on unwanted displacement and attachment of wear debris and material compounds from one surface on to the other (see Fig. 1.3). Adhesion of the workpiece material on the tools causes an increase in the friction forces and process forces. Surface quality of the workpiece decreases. Tool life is decreased as well, because adhesion leads to alternating stresses in the tool surface that leads to tool fatigue near the surface where cracks develop, grow and unite, causing tool material to break out (Klocke *et al.* 2001a, Cartier *et al.* 2003, Anderson 1995). Adhesion may occur with insufficient lubrication (Klocke *et al.* 2001a, Sergejev *et al.* 2011, Klocke *et al.* 2005, Stolarski 1990, Cartier *et al.* 2003). The material transferred to the tool by adhesion has a hardness that is higher by a factor of 2.5 compared to the soft-annealed material at the start of the test. Adhesion growth on the test pieces reaches a standstill at a given time when the competing processes of adhesion formation and abrasion cancel each other out through insufficient mechanical stability within the adhesion (Klocke *et al.* 2005). Macroscopic adhesion (which leads to tool failure) only occurs when there is no longer any coating on the tool surface (Klocke *et al.* 2005).

1.4.3 Fatigue wear of the punch and microcracking of the coating

The hard brittle ceramic coating cannot follow the deformation of the tool and cyclic loading may cause cracking (Klocke *et al.* 2001b). The formation of micro-cracks is the first phase of coating failure. Another reason for cracking of the coating can be excessive tensile or compressive stresses within the coating (Stolarski 1990, Cartier *et al.* 2003) or detachment of the coating as discrete areas due to cracks initiated from droplets in the coating or impurities at the coating and substrate interface (Wiklund et al. 1999, Gerth *et al.* 2009). With its ceramic material behavior, the coating is much more prone to failure through cyclic tensile stress (Klocke *et al.* 2001b).

Fractures, macro- and micro-chipping in substrate material can destroy the cutting edges of the tool. Alternating stresses on the tool surface will lead to the development of fatigue cracks near the surface of the tool (Klocke *et al*. 2001a). Cracks develop, grow and unite, which will eventually lead to material break-out. Friction contributes significantly to the of crack development on the shaft area of the punch through fatigue induced by adhesion (Veinthal *et al.* 2014). High toughness of the HSS steels is required to resist fatigue (Leskovšek *et al.* 1997).

1.5 Objectives of the thesis

Fast wear of tools demands frequent maintenance, which causes machine downtime and high tool service expenses. Frequently the maintenance reasons of fineblanking tools are connected to the wear of the punches. According to the literature, certain PVD coatings may extend the fineblanking punch life-time considerably. Hence, *the main objective of the thesis is focused on the analysis of the wear mechanism and the improvement of the coated punch wear resistance through finding the best coating from the perspective PVD coatings*. Better wear resistance would decrease the financial cost of tools. Resulting from the main scope of the study, the following objectives were addressed:

1. to study the wear mechanism of fineblanking punches in order to strive towards competent and conscious selection of the coatings for fineblanking;
2. to develop a fineblanking field test method for comparing the wear resistance of different PVD coatings;
3. to analyze the PVD coating properties with regard to connecting coating characteristics with performance at the industrial fineblanking field tests.

2 MATERIALS AND METHODS

2.1 Preparation of specimens and industrial punches

Böhler S390 Microclean PM high speed steel (HSS) with its good wear resistance and toughness values was used for substrate material. The HSS block followed a recommended heat treatment process in a vacuum furnace to the hardness 62-65 HRC depending on the specific procedure for the selected batch.

From the HSS block, punches were cut to shape using Wire Electrical Discharge Machining (EDM) in a company producing fineblanking tools. Somewhat different preparation routes were used for the punches described in Paper I, Paper A and Paper III. In Paper I and Paper A the surface of the punches is finished using the grinding technique (GR-punches) and the punches have a chamfer at the cutting edge. In Paper III the punches are complex-shaped and therefore finished using the microblasting technique (MB-punches); punches are sharp, i.e. without the chamfer. Details regarding the industrial punches involved with the study are presented in Table 2.1.

The experimental tools were prepared following the common practice route, i.e. controlling the EDM treatment or the microblasting technique of the punches was not the subject of the study.

Table 2.1 Characteristics of the experimental punches

	Punch	**Finishing treatment**	**Coating and thickness, µm**	**Surface roughness *Ra*, µm**	**Chamfer**
PAPER I, PAPER A	GR-H-punch	grinding type H	TiCN (3.0)	0.57	yes
	GR-H-punch	grinding type H	AlCrN (1.4)	0.33	yes
	GR-M-punch	grinding type M	TiCN (3.0)	0.16	yes
	GR-M-punch	grinding type M	AlCrN (1.4)	0.22	yes
PAPER III	MB-punch	microblasting	TiCN (3.5), nACo (2.5), nACRo (3.3)	0.6-0.9	no
	MB-punch	microblasting	AlCrN (2.1) + DLC2 (0.8)	0.6-0.8	no

Laboratory specimens were prepared by cutting the Böhler HSS S390 into the requested size and heat treating the specimens to hardness 64±1 HRC. Polished specimens were produced using a standard metallographic preparation technique. Additionally, specimens were prepared using a surface finish similar to that of the punches. Microblasting was used to prepare substrates similar to the MB-punches for the evaluation of coating adhesion and grinding was used to prepare substrates similar to GR-punches.

Laboratory specimens from the hard metal WC-Co (WC-10 %) were polished to mirror-finish and coated for the determination of CoF (Paper II), hardness (*H*) and the modulus of elasticity (*E*) of the coating (Paper III) (see specific surface preparation before instrumented indentation in section 2.4).

2.2 Deposition of PVD coatings

Two types of grinding for the GR-punches were used (H and M) prior to coating deposition (Paper I and Paper A). The coating TiCN was deposited in TUT and the AlCrN in Oerlikon Balzers.

The MB-punches in Paper III were pre-treated with microblasting to activate and clean the surface. Hard coatings TiCN, nACo and nACRo were deposited in TUT using PVD equipment Platit π80 with LAteral Rotating ARC-Cathode technology. The MB-punches with AlCrN + DLC2 top layer were deposited in DMX France using the Platit PVD equipment.

The lubricating films of DLC, Al_2O_3 and Ni-WS_2 studied in Paper II were deposited respectively in TUT (PVD equipment Platit π80), University of Tartu (ALD reactor) and Clausthal University (electrodeposition technique).

The deposition temperature for all of the coatings was below the tempering temperature of the HSS substrate. Full details regarding the deposition procedures are presented in Papers I-III.

2.3 Characterization of coating adhesion

Testing the adhesion of thin films is one of the most important and at the same time difficult tasks of surface engineering (Ollendorf *et al.* 1999, Bouzakis *et al.* 2011b). The well-known Rockwell indentation method with 6-scale (VDI Normen 1991) and 4-scale (CEN 1071-8:2004) classification was employed in this study.

The scratch test enables characterizing the adhesion on different levels using critical loads (Vaz *et al.* 2000). The critical load is influenced by the substrate and usually increases with substrate hardness and coating thickness, and decreases with increasing surface roughness (Larsson 1996). The MB-punches had relatively high surface roughness (see Table 2.1), however the ISO standard (EVS-EN 1071-3:2005) limits the scratch test application to Ra < 0.5 µm. Therefore, scratch testing of the coatings was not used.

The two tests have a major drawback that both the coating and the substrate properties determine the results of the tests. Therefore these tests measure only the properties of a certain coating and a substrate combination (Klocke *et al.* 2001a, Holmberg *et al.* 2009).

2.4 Mechanical properties of PVD coatings

Nanohardness and modulus of elasticity were measured from the coatings deposited onto polished WC-Co substrates. Before instrumented indentation the coatings were polished in 0.05 µm Al_2O_3 slurry to reduce the influence of deposition droplets on the surface. Indentations were done using MTS Nano Indenter XP with an unused Berkovich indenter. Loads of 20, 30 and 50 mN in series of minimum 20 qualified measurements were used. The modulus of elasticity was calculated according to Oliver-Pharr (Oliver *et al.* 1992) and following the technical specification procedure (CEN/TS 1071-7:2003).

2.5 Reciprocating sliding experiments

Fineblanking punches undergo sliding wear under high contact pressures forming a friction pair “steel – PVD coating”. Tribological properties of the coatings were determined using the reciprocating sliding test with a CETR UMT-2 universal tribometer (Paper II and III) and with a tribometer Wazau SVT500 (Paper A). Spheres, different in size and chemical composition, were used as counter bodies to the PVD coatings. The hardened steel 100Cr6 was most similar to the sliding pair at fineblanking, however since the hardness of steel is orders lower than that of the coatings, relatively high wear of the steel ball was noticed (Paper A and unpublished observations). Tungsten carbide WC-Co counter body has the highest Young’s modulus, thus enabling the highest contact pressures, however the chemical stability of the HM was unsatisfactory (Paper II). The abrasive wear rate of the coatings (Paper III) was evaluated using the alumina counter body since it enabled high abrasive power and wear of the coatings in reasonable time together with providing chemical stability – positive arguments previously also reported by other authors (Faga *et al.* 2007, Podgornik *et al.* 2011, Paper B). The test parameters are shown in Table 2.2.

Table 2.2 Tribological test materials and parameters

Test type	**Reciprocating sliding (Paper A)**	**Reciprocating sliding (Paper II)**	**Reciprocating sliding (Paper III)**	**Reciprocating sliding (unpublished)**
Substrate	HSS S390	WC-Co	HSS S390	HSS S390
Coating	TiCN (TUT), AlCrN (Balzers)	TiN, TiCN, nACo + films DLC, Al_2O_3, Ni-WS_2	TiCN, nACRo, nACo	TiCN, nACRo, nACo
Counter body	10 mm 100Cr6	3 mm Al_2O_3 and WC-Co	10 mm Al_2O_3	10 mm Al_2O_3 and 100Cr6
Measured properties	CoF – dry and lubricated	CoF (dry), depth of the wear scar	wear rate	CoF (dry)
Test parameters:				
contact force	20 N	2 N	9.81 N	9.81 N
frequency	8 Hz	5 Hz	5 Hz	5 Hz
stroke length	4 mm	1 mm	2 mm	2 mm
distance	120 m	6 m	6 / 12 m	6 m

2.6 Fineblanking field tests

Industrial field tests were conducted in a fineblanking enterprise using a hydraulic fineblanking press HFA4500 *plus* from Feintool. A special fine-blanking lubricant used was supplied by W.L. TriboTechnik. The steel strip material was 4.0 mm soft annealed C60 (Paper I, Paper A) and 2.4 mm cold-rolled S420MC (Paper III). The shape of the experimental GR-punches is given in Figure 2.1. The exact shape of the MB-punches is confidential information, however the fraction of the punch face is shown in Figure 2.2-a.

Wear of the punches was assessed in consideration of the punch geometry and row in the die. The wear measurement method employed in Kulper (Kulper 2009), Paper A, Paper I and III and fully described in Paper III used the stereomicroscope SteREO Discovery.V20 from Zeiss along with OmniMet image analysis software from Buehler. Schematic side view of the punch is presented in Figure 2.2-b. The working range represents the extent of the sliding contact with the steel strip during fine-blanking. Cutting edge of the punch is subjected to wear and during reconditioning it is removed. Worn area of the coating was considered to be equal to the surface area of the revealed substrate of the punch (coating failed area) (see Fig. 2.2-b). Sometimes the punch exhibits areas of small discrete coating detachment (in Fig. 2.2 the areas are exaggerated in size). However, these areas are excluded from the worn area calculation.

Figure 2.1 Un-coated GR-punch used in the field tests in Paper I and Paper A (Paper A).

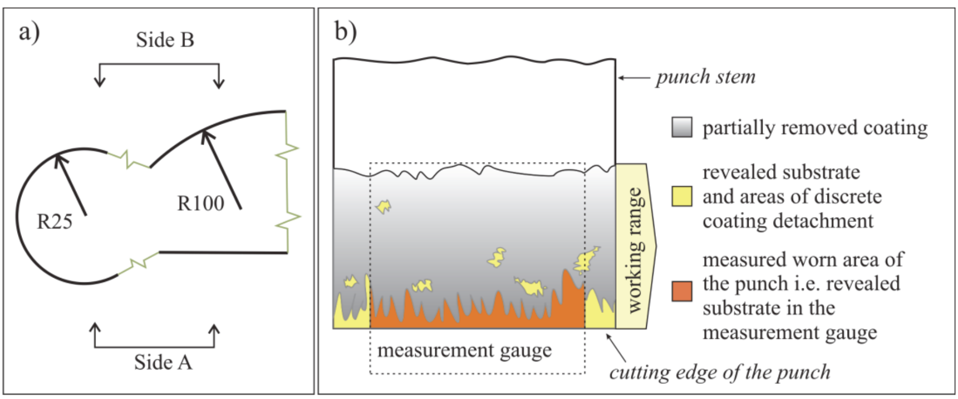

Figure 2.2 Fraction of the face of the MB-punch with representative sides A and B, radius R is given in mm (a) and the schematic method for the coating worn area measurement on industrial punches (b) (Paper III).

3 MECHANICAL AND TRIBOLOGICAL PROPERTIES OF PVD COATINGS

The following coating properties are considered to be influencing the coating performance at fineblanking punches: coating modulus of elasticity and hardness, its tribological properties and coating adhesion.

3.1 Mechanical properties of the coatings

The practical applicability of the PVD coatings depends on the order of magnitude of their main mechanical properties, such as hardness (*H*), modulus of elasticity (*E*), not only showing the characteristics of the coating, but allowing the assessment and comparison of coating wear resistance on the basis of the ratio of hardness to the elastic modulus.

Studies (Leyland *et al.* 2000, Affonso 2006) have found that the higher H/E ratio (*elastic strain to failure*) of the coating leads to reduction in wear, assuming that hardness is sufficently high. The elastic modulus should be similar to the underlying substrate material, allowing the coating to deform together with the substrate without cracking or debonding. However, Musil showed that coatings with different hardness exhibit approximately constant H/E ratios (Musil *et al.* 2002). Therefore, additional alternative ratios of hardness to elastic modulus should be used for better coating characterization.

The H/E^2 ratio (*resistance to plastic indentation*) is expected to correlate well with resistance to abrasive and erosive wear (Joslin *et al.* 1990). The high H/E^2 ratio is the indication of the material's better ability to resist permanent damage.

Furthermore, H^3/E^2 ratio (*resistance to plastic deformation*) is reported to correlate with the wear resistance of the hard coatings (Tsui *et al.* 1995). Higher H^3/E^2 ratio means higher ability of the coating to dissipate energy due to plastic deformation during loading.

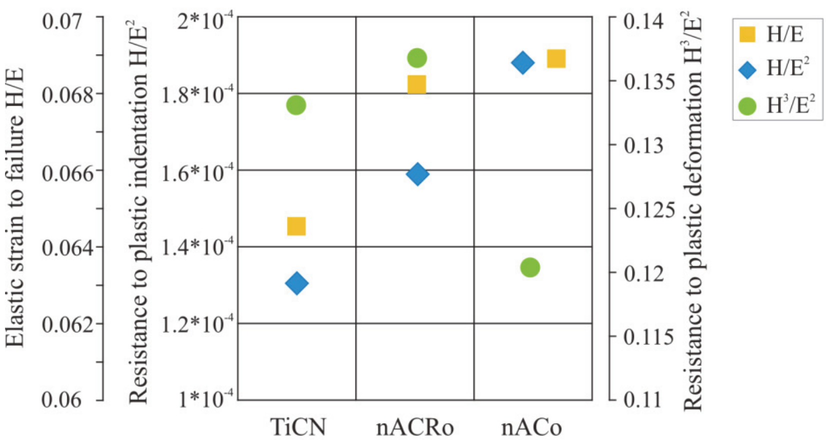

Figure 3.1 Characteristic ratios of the selected PVD coatings (Paper III).

Table 3.1 Mechanical properties of the selected PVD coatings

Coating	**Coating type**	**Coating thickness, μm**	***E*, GPa**	***H*, GPa**	***H*/*E*, 10^{-1}**	***H*/*E*^{2}, 10^{-3}**	***H*^{3}/*E*^{2}**
TiCN	gradient	3.5	494±24	31.9±1.4	0.646	0.131	0.133
nACRo	gradient nano-composite	3.3	429±16	29.3±0.6	0.683	0.159	0.137
nACo	multilayer nano-composite	2.5	367±8	25.3±1.9	0.689	0.188	0.120

The mechanical properties of the studied TiCN, nACo and nACRo thin hard coatings and the values of hardness to elastic modulus ratio are given in Table 3.1 and graphically shown in Figure 3.1. The H/E^2 ratio distinguishes the coatings and leads to a conclusion that the nACo coating has the tendency to higher abrasive and erosive wear resistance among the studied coatings. However, the resistance to plastic deformation (H^3/E^2) of the nACo coating is the lowest compared with the TiCN and nACRo coatings. If all three ratios are taken into consideration, the nACRo coating seems to be the most promising candidate for the highest performance in the conditions of intensive abrasive and erosive wear.

3.2 Coating adhesion

Coated tools with PVD-films of almost the same mechanical properties may perform differently. This effect can be attributed to the film adhesion. The films' adhesion is one of the most pivotal properties affecting the cutting performance and life span of coated tools (Bouzakis *et al.* 2011b).

Adhesion is influenced by the substrate hardness, surface quality and microstructure (Podgornik *et al.* 2011, Vidakis *et al.* 2003). Often substrate pre-treatment and adhesive layers are used to enhance the films' adhesion. In order to optimize adhesion, the hardness of the interlayer should be close to the hardness of the substrate. The elastic modulus of the metallic interlayer does not affect the adhesion as much as its hardness (Gerth *et al.* 2008).

Rockwell C indentation enables evaluation of two distinctive properties of the coated compound, i.e. the interfacial adhesion as well as the film brittleness and cohesion (Vidakis *et al.* 2003). The coated specimen may be adequately evaluated by means of conventional optical microscopy, however the quality control method becomes significantly more effective when the SEM is utilized (Vidakis *et al.* 2003).

Experimentally, the coating adhesion was characterized on polished and microblasted surfaces. The coated polished samples are considered a standard measure for quality assessment and coating thickness measurement. However, from the application perspective, adhesion on MB-punches may not be compared with adhesion on polished substrates. Therefore, microblasted specimens were used for evaluating coating adhesion. Table 3.2 shows a tendency that on microblasted surfaces the adhesion is inferior compared to the polished substrate. Figure 3.2 shows a SEM image of the nACo coating. Using greater magnification, an area where the coating is detached is shown on the left. The SiC particle is likely to be embedded onto the substrate during the microblasting operation. Presence of such particles on the coating-substrate interface undoubtedly deteriorates the adhesion quality. Moreover, from such impurities cracking of the coating may be initiated, explaining the inferiority of coating adhesion on microblasted substrates.

Table 3.2 Coating adhesion

Coating	Polished specimen	Microblasted specimen, *Ra* = 0.4 μm
TiCN	HF2	HF4
nACRo	HF3	HF3
nACo	HF3	HF3

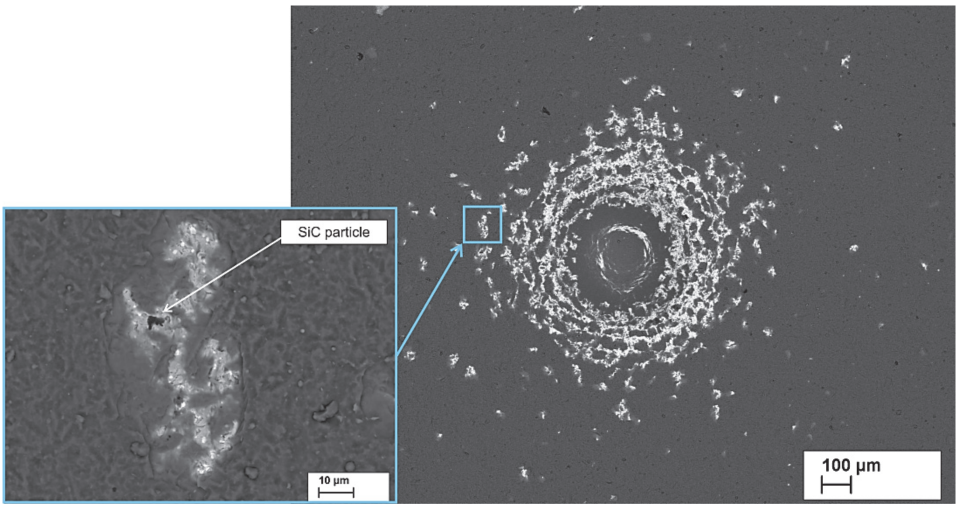

Figure 3.2 SEM image of Rockwell C indent characterizing the adhesion of the nACo coating to the microblasted S390 substrate (surface *Ra* = 0.4 μm).

3.3 Tribological properties of the coatings

It was quite challenging to select test parameters for the determination of tribological properties. In Paper II the TiCN and the nACo coating were compared using the 3 mm balls, however the wear track was poorly distinguishable. Hence, a 10 mm ball was chosen for tribological tests in Paper III. Because of the remarkably high wear of the nACo coating (see wear rates from Table 3.3), a relatively low force of 9.81 N was used. Nevertheless, the wear of the nACo coating was significantly higher than TiCN or nACRo, therefore shortened experimental time was used for nACo (see Paper III). Tests were conducted on the polished specimens because it is difficult to measure the depth of the wear with higher surface roughness (ground or microblasted surfaces).

Table 3.3 Tribological properties of the selected coatings

Coating	**CoF, ball diameter 10 mm**		**Wear rate, 10^{-6} mm^3/N·m (Paper III)**	**CoF, ball diameter 3 mm (Paper II)**	
	Al_2O_3	**100Cr6**		**Al_2O_3**	**WC-Co**
TiCN	0.32	0.67	0.25	0.16	0.16
nACRo	0.45	0.55	0.22	-	-
nACo	0.75	0.78	7.59	0.84	0.66
TiN	-	-	-	0.54	0.54
Al_2O_3 top film	-	-	-	Top film did not affect the CoF – it remained the same as for base coatings	
Ni-WS_2 top film	-	-	-	Depending on the base coating and counter body 0.35-0.78	
DLC top film	-	-	-	Depending on the base coating 0.16-0.18	

As can be seen from Table 3.3, nACo has the highest coefficient of friction (CoF) and the wear rate independent of the used counter body chemical composition or size. Regarding the wear rate and CoF with 10 mm balls, it is difficult to compare TiCN and nACRo since with the alumina ball, TiCN has lower CoF, however with the steel ball, nACRo has lower CoF. Although somewhat lower for nACRo, the latter coatings have similar wear rates.

The results of the wear rate are is in good agreement with the resistance to the plastic deformation (H^3/E^2) ratios, see Figure 3.1. This indicates that the contact pressure applied at the reciprocating sliding test probably exceeded the elastic deformation limit of the nACo coating at the largest extent.

In Paper II the TiN, TiCN and nACo coatings and lubricating films (Al_2O_3, Ni-WS_2 and DLC) are compared on the basis of their CoF and wear. The Al_2O_3 film added no tribological advantage to the base coatings. An additional film of Ni-WS_2 was able to provide lower CoF and good protection against wear on the TiN and TiCN base coatings, however on the nACo base coating, the behavior was dependent on the counter ball. Further studies are required before the industrial application of the lubricating film Ni-WS_2. The DLC top film was promising, resulting in low CoF and wear on all of the tested base coatings. Hogmark *et al.* (Hogmark *et al.* 2000) report that under suitable conditions, DLC can provide a combination of good wear and corrosion resistance and low friction, however the main limitation can be poor thermal stability. Out of the top films the DLC film was chosen for industrial field tests because of its promising tribological properties and commercial availability.

4 FINEBLANKING FIELD TESTS

4.1 Development of the field testing method

To assess the coating performance it is important to test the coatings in a tribological system, which is as close to the application as possible. Field testing is a major challenge since the results are always influenced by many factors involved in the production. However, it is essential to test the wear performance in the original application. The goal in the development of the field test method was to minimize the number of influencing factors and to achieve comparable results for different coatings or pre-treatments. In Paper A and Paper III, an industrial field testing method is employed which enables the performance of different coatings or surface treatments to be compared on an industrial scale. The technique is relatively simple, however visible wear of the coatings (see Fig. 4.1) and multiple row tools are required to use the method.

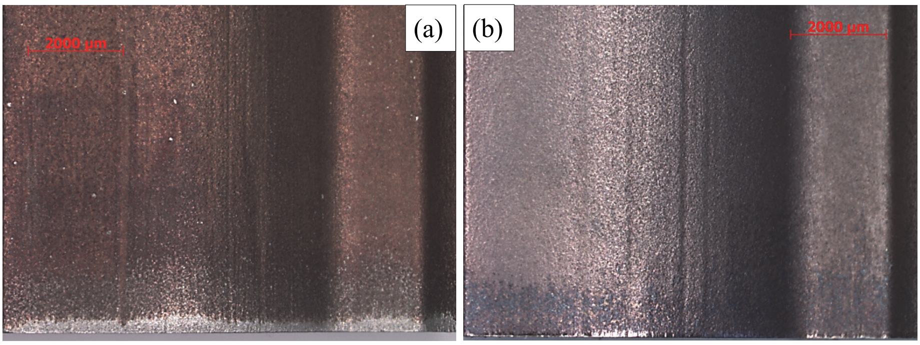

Figure 4.1 Coating wear measurement is suitable for tools where wear is visible (a), however unsuitable at extremely low wear (b).

The wear of the coatings was measured using the OmniMet image analysis. Alternatively, in conventional blanking the wear evolution has been previously measured with a tactile stylus method (So *et al.* 2012) or the coordinate measuring unit (Tšinjan 2012). However, the methods were found unsuitable for the chosen fineblanking punches where the wear is in the magnitude of a few micrometers which would be difficult to detect. Furthermore, the adhesion of workpiece material onto the substrate could give misleading information at the profile measurement.

Different coatings may have different appearances with regard to the color. For example, the TiCN has a distinguishable red-copper color and therefore the wear or adhesion on the tools may be visually well detected. The nanocomposites are both grey. From Paper A, it was identified that the operators tend to misjudge the coating wear when asked to compare the wear of the AlCrN coating with that of TiCN. The reason could be that in the case of TiCN the contrast in the punch wear is visually more distinguishable and this leads to a misconception of more intense wear. Therefore, visual judgement of the coating wear may be very misleading and should not be used in the assessment of the performance of different coatings at their application.

To exclude the influence of factors like punch location (row), steel strip batch number or different operators of the tool, the following means (originally presented and fully described in Paper III) were applied in the developed field testing method:

- The heat treatment, EDM, microblasting and handling were similar for the set of test punches.
- A *multiple row* progressive *tool* enabled using a set of punches working at the same time in similar conditions.
  This measure guarantees that the test punches are working in comparable conditions and excludes possible variations in the sheet metal batch, the number of strokes, factory temperature and the operator.
- Conducting *repetitive tests* since one single test may give misleading results. Furthermore, the behaviour of fully coated punches is likely to be different from the reconditioned ones, i.e. the face of the punch is left uncoated after reconditioning.
- High wear might be caused by specific rows, therefore it was necessary to *rearrange the punches* in between repetitive tests.
- Wear from specific field tests was converted into *relative percentage* in order to enable comparing wear results from repetitive trials where a different number of strokes was conducted with the punches.

4.2 Wear mechanism of the coated fineblanking punch

Wear mechanism of the punch was studied on the ground GR-punches with the chamfer at the cutting edge (Paper I) and the microblasted MB-punches without the chamfer (used at the industrial field tests described in Paper III). Deficiency of the chamfer induces higher stresses at the punch cutting edge, thus complicating the working conditions. Wear mechanism was outside the scope of Paper III, therefore the mechanism is not described in the article, however it is discussed for the first time in the present thesis.

At the tip of the punch, the working conditions are most severe and contact with the blanking material is the longest. The coating is most worn close to the cutting edge (Fig. 4.2). The wear intensity decreases with the increasing distance from the cutting edge. Following this concept, the wear mechanism was divided into different stages with respect to the distance from the punch cutting edge. Figure 4.2 (from Paper I) shows the distribution of the wear stages I, II and III.

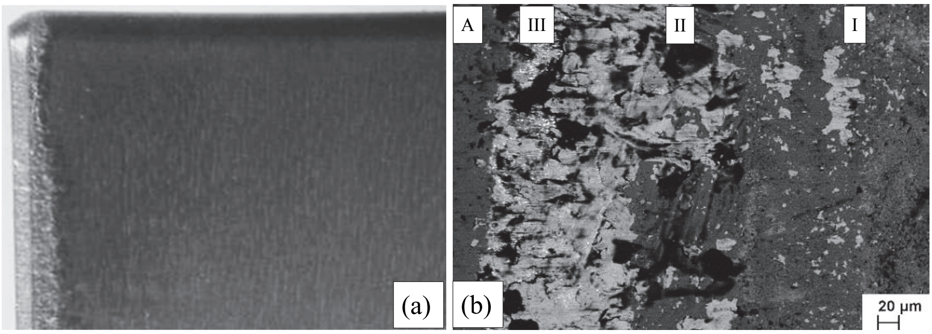

Figure 4.2 SEM photograph of the punch (a) and its close-up at greater magnification (b) (Paper I): I – wear stage 1, II – wear stage 2; III – wear stage 3 and A – chamfer of the punch.

According to Paper I, the wear mechanism of the punch is characterized by three stages where different wear types dominate (see Figures 4.2 and 4.3):

Stage 1: Carbides and non-metallic inclusions of sheet metal and worn abrasive particles induce the abrasive wear of the punch. In stage I the main mechanism of wear is abrasive due to good lubrication and few contact asperities. Adhesion and fatigue are insignificant.

Stage 2: Lubrication conditions have changed due to the decrease of punch surface roughness. The adhesion of sheet metal to the punch is becoming dominant, leading to greater stresses and higher contact temperature resulting from increased friction. At the end of stage 2 the coating is fully removed from the punch, revealing the substrate material. In stage 2 adhesive wear becomes dominant.

Stage 3: During stage 3 intensive adhesion can cause elevation in the stresses and temperature in the surface layer of the punch. The increase of force F might cause formation of a fatigue crack leading to chipping or breakage of the punch tip.

The described wear mechanism confirms the importance of having good lubrication and optimized surface roughness in order to prevent the intensive adhesive wear in stage 2. Furthermore, it is also important to prevent the amount of abrasive particles in the fineblanking tribosystem, for example by using a blanking material with the same mechanical properties but with a lower carbon content and carbide amount. During maintenance attention should be focused on cleaning the tools after grinding in order to avoid the presence of abrasive grinding particles on the tool surfaces.

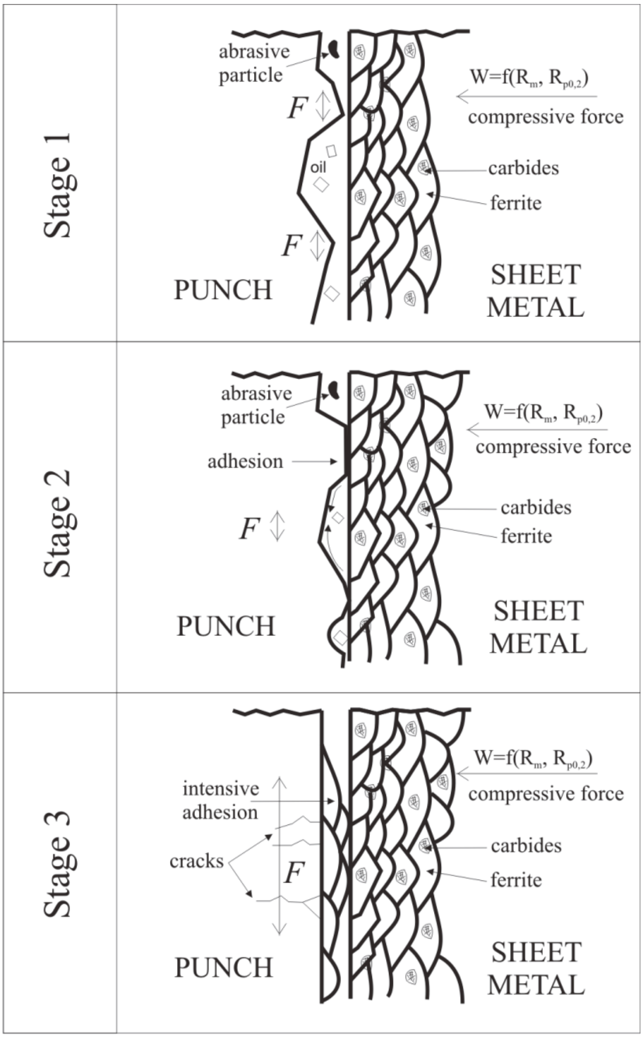

Figure 4.3 Three stages characterizing the punch wear mechanism (Paper I).

Coating removal mechanism was similar on the microblasted and the ground (MB- and GR-) punches. However, discrete coating detachment of the MB-punches was noticed at the industrial field tests. Figure 4.3 presents a SEM image of a worn industrial MB-punch. In addition to the coating failed area close to the cutting edge of the punch, small detached flakes of the coating and adhesion of workpiece material are visible on the punch side (Fig. 4.3-a). All of the MB-punches independent of the coating exhibited coating removal in discrete areas (a mechanism also reported by Gerth (Gerth *et al.* 2009)).

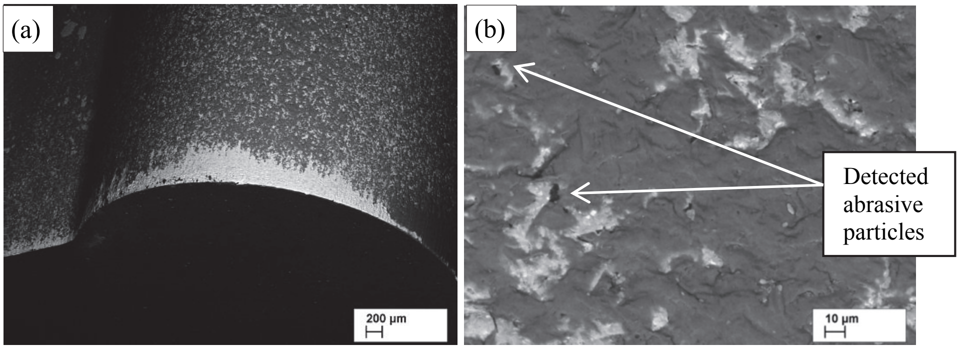

Figure 4.3 SEM image of the worn punch with the nACRo coating at magnifications 20x (a) and 500x (b).

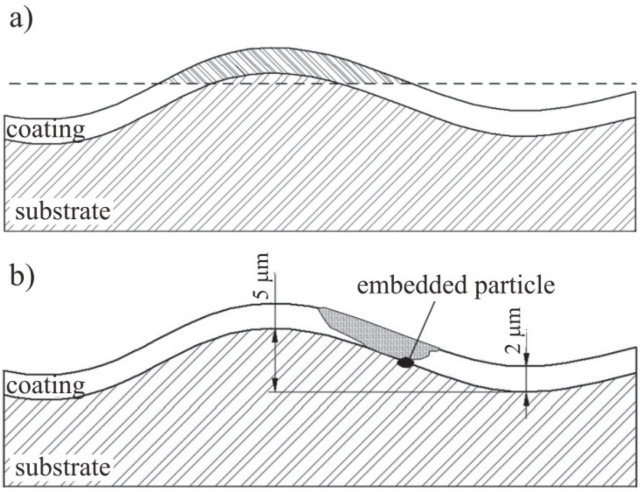

Figure 4.4 Theories regarding detachment of the coating from the discrete areas: a – coating is removed because of the high surface roughness *Rz*, b – coating detachment starts from impurities at the coating-substrate interface.

Mechanism of coating detachment at the discrete areas could be associated with various theories. Surface roughness of the punches is relatively high, moreover, the *Rz* values exceed the coating thickness values. Higher peaks of the coating could wear abrasively, revealing the substrate in the discrete areas (Fig. 4.4, mechanism a). However, the theory is not supported by the decrease of surface roughness nor the SEM observations. SEM studies show that not only the peaks of the coating were detached; the coating was also missing from the valleys of the surface leading to the next theory. Using the EDX analysis, an Al_2O_3 particle was found beneath the missing coating on the punch substrate, indicating that the cracking of the coating could have started from the embedded particles on the substrate (Figs. 4.3-b and 4.4, mechanism b). The particles most likely originated from microblasting, which emphasizes that the surfaces must be free from abrasives and other residues before coating (Oerlikon Balzers). The second theory is also supported by previous studies (Gerth *et al.* 2009, Gerth 2012, Wiklund *et al.* 1999, Zoestbergen *et al.* 2002), indicating that irregularities in the interface combined with compressive residual stress of the coating could be a starting point for cracking and coating detachment.

4.3 Surface topography of the fineblanking punch

Surface topography plays an important role in terms of enabling good lubrication of the surfaces, i.e. having so called "oil pockets" where the oil is preserved and carried. However, if the surfaces are too rough, the tribofilms do not grow thick enough to separate the surfaces and the work material is abrasively worn during sliding (Heinrichs *et al.* 2012). A study from Harlin *et al*. reports that the surface roughness of the coating is of importance in order to control the initial material pick-up tendency and thus the friction characteristics in a sliding contact (Harlin *et al.* 2006).

In Paper A, industrial GR-H-punches (high *Ra*) and GR-M-punches (low *Ra*) are compared at fineblanking field tests. The experimental CoF measurements showed that higher surface roughnesses lead to higher CoF in dry conditons (see Table 4.1), implying that the wear at industrial trials should also increase but this was not the case. In fact, the worn area measured was found twice higher for the lower surface roughness GR-M-punches. In the lubricated tribological tests the obtained values for CoF were similar for surfaces with low and high *Ra*. The lubricant fills the surface irregularities and pores. With higher Ra values more oil is preserved on the punch surface leading to better protection against wear. Furthermore, the theory was supported by the company experience where ground punches with low surface roughness (*Ra* ~ 0.1-0.15 μm) lead to seizure of the punches due to lack of the lubrication at the blanking material and tool inferface. The failure was corrected by increasing the punch surface roughness.

In conclusion, surface topography is a subject of major influence on the wear and therefore needs more attention than provided by the present study. This is supported by research from Podgornik and his colleagues who report that the tool preparation affects the wear performance more than the coating characteristics (Podgornik *et al.* 2011).

4.4 Influence of different PVD coatings on the punch life-time

4.4.1 Selection principles of the studied PVD coatings

Nanocomposite coatings nACRo and nACo from Platit were selected for the experiments together with the well-known multipurpose TiCN (TiCN-MP). The studied coatings were selected based on the specifications given by Platit (Platit AG 2014) and also on the possibility and competence of TUT PVD Laboratory to prepare the coatings. The TiCN-MP coating is a well-known and widely used multipurpose coating with limited maximum usage temperature at 400 ºC (Platit TiCN-MP 2014). TiCN is a well established widely used coating making it the perfect base for comparison of different coatings. Nanocomposites are characterized by extremely high nanohardness at very high toughness values and extremely high heat resistance reaching 1100–1200 ºC (Platit nanostructures 2014). High hardness of the nanocomposites was promising to achieve good wear resistance at the first stage of wear where the abrasive mechanism dominates (see section 4.2). Additionally, the chosen nanocomposite coatings contain elements like Cr, Ti or Al, which are all recognized by previous studies based on their excellent characteristics (see section 1.3).

4.4.2 Relative wear of different PVD coatings

In Paper A, the GR-M-punches and GR-H-punches with Alcrona (Oerlikon Balzers) and TiCN coating are compared. The results show that the worn areas are dependent on the grinding type, however wear amount was similar for different coating compositions (Table 4.1).

Table 4.1 Surface areas of worn punches (Paper A)

Punch type	Surface roughness *Ra*, µm	CoF (dry)	CoF (oil)	Worn area ± STDEV
TiCN H	0.57	0.33 ± 0.04	0.10 ± 0.02	1.94 ± 0.42
TiCN M	0.16	0.28 ± 0.04	0.10 ± 0.02	4.00 ± 1.20
Alcrona H	0.33	0.34 ± 0.05	0.10 ± 0.02	2.15 ± 0.18
Alcrona M	0.22	0.27 ± 0.03	0.12 ± 0.02	4.20 ± 0.86

In Paper III the MB-punches were prepared using the same surface finish technique (microblasting) and the focus was set to comparing the wear performance of different PVD coatings. The number of strokes from repetitive tests in Paper III varied from 20 500 to 45 000. Wear results within each test were converted into *relative wear* percentage in order to neglect possible wear differences derived from material batch or the number of strokes. The calculation method of the coating relative wear w_i is described in full extent in Paper III.

Figure 4.6 presents the relative wear data as raw data from five repetitive industrial field tests made with a six-row (R1-R6) tool (Paper III). Each repetitive test consists of the results from six punches with three coatings. Coatings are shown in Figure 4.6 with different color and pattern scheme. Coated punches are rearranged in between the repetitive trials to achieve reliable results and for that reason each row (R) consists of different coating columns. Resulting from five repetitive experiments it was revealed that in row 1 (R1) the wear was always almost two times higher. Exceptionally, at field test no. 5 the wear in R1 is comparable with other rows. The reason is likely to be connected to the changed guide plate. Further analysis neglected the results from R1 concerning field tests 1–4 since increased wear at these tests in that specific row is most likely caused by the tool setup or design and not strictly related to the coating composition or properties.

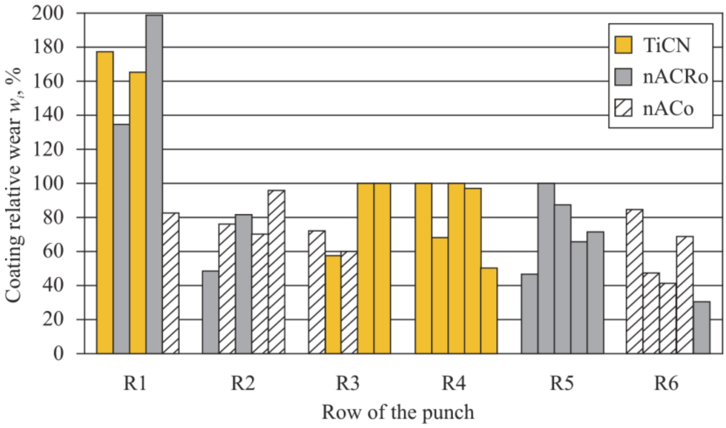

Figure 4.6 Wear results throughout the 5 field tests. For each row 5 columns are given representing tests no. 1 - 5 from left to right, respectively (Paper III).

Figure 4.7 shows the quantitative analysis of the data in Figure 4.6 in the form of the average, median and upper-lower limits of wear for the tested coatings. Test results show correlation to the ratio elastic strain to failure *H*/*E* (Fig. 3.1). The TiCN coating shows the highest wear, however it is difficult to differentiate nACRo from nACo on the basis of the industrial tests. The nACRo coating showed unstable behavior by having excellent wear resistance at some tests while being the poorest at other tests. TiCN can also be good at some tests, however using only the TiCN coatings at the production would probably result in the decrease of the overall punch lifetime compared with nACRo or nACo. Accordingly, it is not important to have high hardness of the coating but low elastic modulus to keep the stresses inside the coating low. There is no connection of the industrial field tests with the reciprocating sliding test with the Al_2O_3 ball and neither is there any direct connection to resistance to plastic indentation (H/E^2) and resistance to plastic deformation (H^3/E^2).

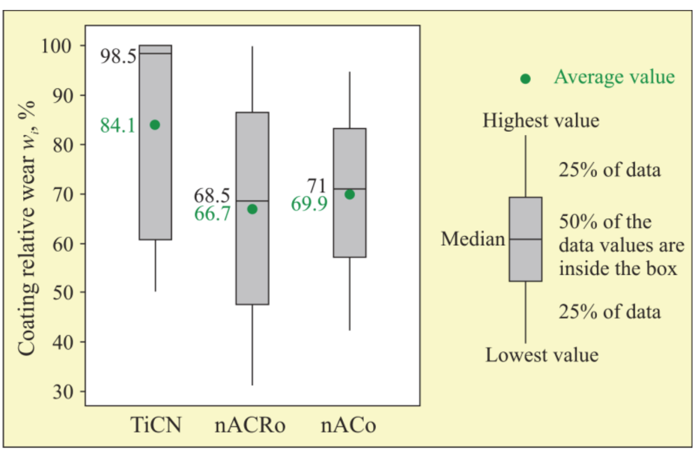

Figure 4.7 Relative wear of coatings at repetitive industrial field tests (Paper III).

From Figure 4.7 it could be estimated that the difference between the average relative wear of the compared coatings is 14-17 %. Comparing only the minimum relative wear values of coatings, the difference between the best (nACRo) and the worst (TiCN) punch is somewhat higher, reaching 19 %. However, comparing only the maximum relative wear values, the difference between nACo (best) and TiCN (worst) is only 5 %.

The tests show that the difference between the average relative wear of PVD coatings is approximately 15 %. However, this percentage may not be directly connected to the life-time of punches (number of strokes). The average percentage is the only indicator of the worn area size for different coatings. Furthermore, the high variation in wear means that sometimes the best coating can also behave like the worst coating. The reasons for high wear variations are discussed in the next section.

4.4.3 Discussion concerning high wear variation at the field tests

Relative wear of each coating varied between the rows and the different tests within a wide range (Figs. 4.6 and 4.7), extending from 50 % up to 70 % difference between the upper and the lower relative wear values within certain coatings. It is most likely that the high dispersion in the results is connected to the punch preparation, i.e. EDM treatment and microblasting (pre-treatment) prior to the PVD coating process. Substrates of the punches were manually microblasted before the coating deposition. With manual blasting it is difficult to guarantee that the topography will be uniform. Moreover, impurities on the substrate, i.e. particles from microblasting which are embedded into the surface may be the cause for cracking and detachment of discrete coating areas (Wiklund *et al.* 1999, Gerth *et al.* 2009), see Figure 4.8.

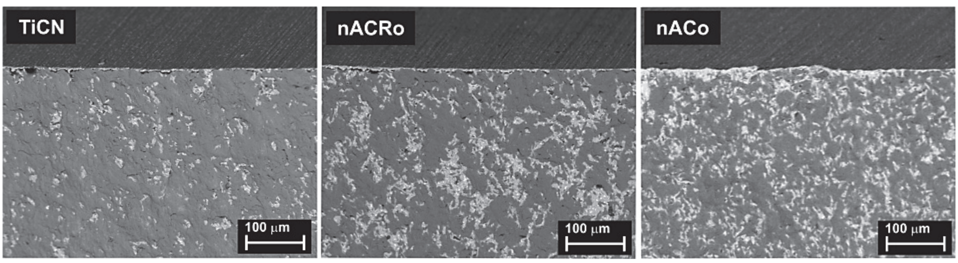

Figure 4.8 Cutting edge of the punch after reconditioning. Discrete coating detachment of the coating is evident on all of the punches irrespective of the coating (Paper III).

Furthermore, the reconditioned punches may have already wear marks due to the nature of the reconditioning procedure. The aim of the reconditioning is to remove the visibly worn areas of the punch and to resharpen the cutting edge. However, the sheet strip thickness (i.e. working range of the punch) is several times higher compared to the worn area height (see Figure 2.2). Hence, the working range of the reconditioned punch coincides with the working range at the previous operation. Therefore, with reconditioned punches the coating close to the cutting edge is not new but already worn and may exhibit coating detachment in discrete areas (Fig. 4.8). The state of the punch may induce difference in the wear rate, however this theory has to be checked by repeated tests with fully coated and reconditioned punches.

Future work should consider better control over the preparation of punches. Excluding coating adhesion variations derived from the EDM process or the following abrasive treatment needs increased attention.

4.5 Surface modification of PVD coating using the DLC top layer

In the Introduction, several studies were referred to that have used top coatings in the creation of advanced coating systems. The conducted wear tests in the laboratory gave promising results in terms of low CoF and wear depth when combining different base coatings with the DLC top coating (Paper II). On that basis, the DLC layer was chosen for the modification of the coatings with the scope of lowering the CoF and improving the wear resistance of the punches.

Punches were coated in DMX France and employed in a fineblanking company. Burr exceeded the allowed limit after 31 000 strokes because of wear of tools. It was difficult to evaluate the condition of the DLC layer with visual inspection (Fig. 4.9), nevertheless using the SEM the DLC layer was observed to be detached from the base coating (Fig. 4.10). Reasons for the poor performance of DLC2 are probably connected to the poor adhesion at the base and top coating interface. The field tests show that the DLC top coating does not seem promising for applications at the fineblanking punches. Furthermore, the results of the experiment seem to be in agreement with previous studies reporting an increase in the forces with the DLC top layer (Podgornik *et al.* 2011, Nyberg *et al.* 2013) and removal of the top DLC layer (Podgornik *et al.* 2011). Poor thermal stability of the DLC coating could have also been the reason for failure, as previously reported by Hogmark *et al.* that the DLC coatings decompose above 300 ºC (Hogmark *et al.* 2000).

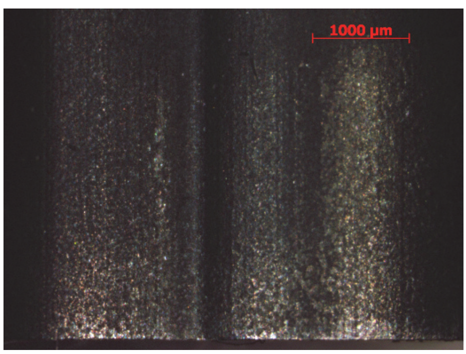

Figure 4.9 Worn industrial punch with AlCrN + DLC2 coating using a stereomicroscope.

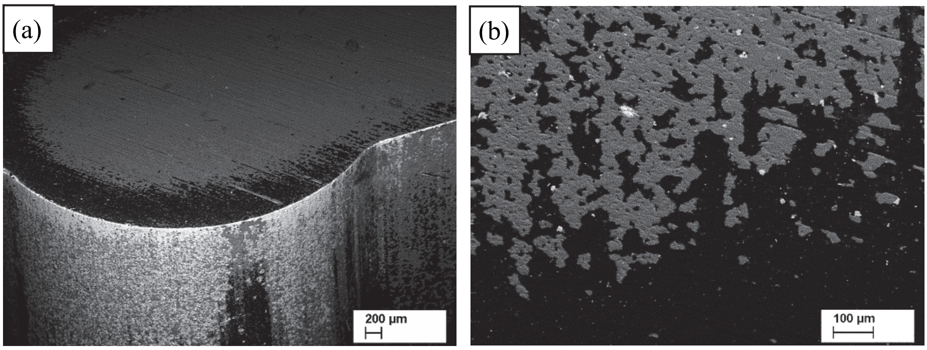

Figure 4.10 SEM image of the industrial punch showing the detachment of the DLC2 top layer from the AlCrN base coating.

5 CONCLUSIONS

The industrial field tests have many aspects which are challenging to control, however only those tests enable the true performance of the tools to be observed. Motivated by this issue present thesis presents several means to overcome the challenges involved with the industrial field tests.

In the scope of the thesis the fineblanking punch wear mechanism was studied and the wear resistance of the PVD coatings was compared using the developed industrial field test method. Conclusions of the thesis may be formulated with respect to the set objectives:

1. Main wear mechanism of the coated punches may be divided into three stages where different wear types dominate. In the first stage abrasive wear of the coating dominates. This is followed by dominating adhesive wear in the second stage where eventually intensive adhesion causes fatigue in the third stage leading to chipping or breaking of the punch.
   In addition to the main wear mechanism punches prepared using the microblasting technique suffered from the mechanism of coating detachment from discrete areas. The theories of previous authors were confirmed by SEM studies revealing that such failure mechanism was caused by impurities (abrasive particles) on the coating and substrate interface.
   Furthermore, surface topography of the punches had high impact on the dominating punch wear mechanism. The microblasted punches had relatively high average surface roughness *Ra*, providing sufficient lubricant entrapment on the punch surface. However, with the ground punches low and high Ra was put to the test and it was found from the industrial field tests that higher Ra was beneficial in providing sufficient lubrication and wear resistance. Punches with low Ra exhibited two times higher wear.
   Altogether the punch wear mechanism was influenced by the surface preparation and topography of the punch and the surface properties to resist abrasive and adhesive wear.

2. For testing the coatings in *comparable conditions and in a tribological system that is as close to the application* as possible, an industrial field testing method was developed. The highest challenge was to avoid and reduce the number of influencing factors (e.g. steel batch number, punch row, influence of tool operator). This was achieved through using a multiple row tool and conducting repetitive tests. Furthermore, a reliable wear assessment technique was required, which was achieved through measuring the average relative wear percentage of the coating, enabling also comparison of the results from repetitive tests with a different number of strokes.

3. Industrial field test results regarding the performance of different coatings were found to be in correlation with the coating *elastic strain to failure H/E* ratio. Coatings with higher *H/E* ratio had better average wear resistance at the fineblanking field tests. Moreover, using the nanocomposite coatings nACo or nACRo, the average relative wear resistance could be increased approximately 15 % compared to using TiCN.
   The field test results did not correlate with the wear rate or coefficient of friction of the coatings obtained using the reciprocating sliding tests in the described form.
   Diamond-Like Carbon (DLC) top coating showed promising results in the laboratory reciprocating sliding test. However, the top layer of DLC2 in a large extent was detached from the punch after industrial field tests and therefore did not improve the wear resistance of fineblanking punches.

The following recommendations were given to the fineblanking company in order to improve the tool life-time:

- With respect to the abrasive wear mechanism, the presence of loose abrasive particles should be avoided by using blanking steels with low carbon content and by proper cleaning of tools during maintenance.
- In terms of the wear mechanism and to avoid adhesive wear it is important to provide sufficient lubrication through selection of punch topography. Fairly high surface roughness *Ra* 0.3-0.6 µm is recommended to ensure the presence of oil entrapment on the punch surface.
- DLC top coating would not improve the wear resistance of punches, however would increase the coating price.
- Coatings with high *H/E* ratio should be preferred for fineblanking punches. Coatings nACo and nACRo should be preferred instead of TiCN. However the tool life-time is a complex of many influencing factors and the coating alone has only limited impact. The field tests have shown that for example the wear of the guide plate or the wear in a specific row of the tool may affect the life-time considerably more.

In the future work the proposed industrial field test method may be utilized for tests with several variables like coating thickness or surface topography to optimize these variables.

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ABSTRACT

Wear of PVD Coatings on Fineblanking Punches

Fineblanking technology is an industrial application based on very specific knowledge and know-how for producing high quality details within one operation sequence. High technicality and precision of the tools is a prerequisite for the process. Extremely low punch and die clearance (0.5 % of workpiece material thickness) and use of counter force and vee-ring force in addition to the cutting force are characteristic of the fineblanking process. The particular features ensure the flatness and high quality of the product sheared edge, at the same time creating difficult working conditions and high contact pressures for the tools. Wear of tools prompts the need for frequent maintenance and causes machine downtime and high tool service expenses.

Often the maintenance reasons of fineblanking tools are connected to the wear of the punches. Studies from other authors have shown that certain Physical Vapour Deposition (PVD) coatings may extend the fineblanking punch life-time considerably. Hence, the PhD studies were focused on the coating wear mechanism analysis and improvement of the punch wear resistance through finding the perspective PVD coatings which could be produced in Tallinn University of Technology.

Field tests are important in experiencing the actual performance of tools. However, they are also complicated due to the nature of many variables influencing the wear results. In order to reduce and avoid the large number of variables at the field tests, a method was developed utilizing the industrial multiple row tool and relative coating wear. These measures enabled to compare results obtained from different tests and to avoid the influence of steel batch or the operator. Furthermore, repetitive trials were conducted with the punches since one single test may give misleading results.

Wear mechanism of punches was explored using the industrial field tests in combination with the SEM studies. The industrial tests involved punches with ground and microblasted finish. The difference in preparation of the punches was derived from the shape of the punches – in certain circumstances (with complex-shaped punches) the preparation of the punches is not technologically possible with grinding. Nevertheless, the wear mechanism studies revealed that for both type of punches three wear mechanisms were present: abrasive, adhesive and fatigue. All of the mechanisms took place simultaneously under the influence of each other, however in different stages of the wear, different mechanisms dominated. At the early beginning of the process, abrasive wear was dominant, followed by adhesive and fatigue wear which eventually lead to chipping or fracture of the punch. High hardness of the coatings is necessary to resist the abrasive mechanism which is the first to take place during fineblanking. Studies regarding the coating wear at fineblanking emphasize the importance of low modulus of elasticity. Therefore using various H to E ratios

described by previous studies was decided to be the basis for ranking the theoretical wear resistance of different PVD coatings.

Furthermore, the mechanism of discrete coating detachment was detected on the microblasted punches. This type of mechanism has been previously described by other authors and in the present study it was confirmed using the SEM and EDX analysis that cracking and detachment of the coatings is started from abrasive particles present at the coating-substrate interface.

Surface topography was found to have major influence on the wear performance. From the industrial field tests with ground punches it was found that surface roughness is important from the perspective of lubricant entrapment onto the punch surface.

Abrasive wear resistance is connected to the hardness (H) of the coating and therefore high hardness of the coating is important from the perspective of abrasive wear resistance. Furthermore, according to different sources coatings with low modulus of elasticity (E) are preferred. Proceeding from these recommendations different ratios of hardness and modulus of elasticity were chosen for theoretical evaluation of coating wear resistance (H/E, H^2/E and H^3/E^2). The average wear resistance of the PVD coated microblasted punches was found to be in correlation to the H/E ratio. Coatings with higher *elastic strain to failure* H/E had better wear resistance at the industrial fineblanking field tests. Ratios H^2/E and H^3/E^2 of the coatings showed no direct correlation to the industrial wear of coatings. Furthermore, the coefficient of friction and the wear rate obtained at reciprocating sliding tests showed no correlation to the field test results, indicating that the industrial wear resistance cannot be predicted using reciprocating sliding tests in that form.

Regarding specific coating compositions, the nanocomposite coatings nACo and nACRo showed approximately 15 % higher wear resistance than TiCN. The Diamond-Like Carbon (DLC2) top layer was detached from the punch and did not improve the punch wear resistance.

In conclusion, the wear of PVD coated fineblanking punches is influenced by several wear mechanisms and in different stages of wear, different mechanisms dominate. The high H/E ratio of the coating may be taken as a reference in the selection of PVD coatings for fineblanking application. In the present study difference between the average wear resistance of the selected coatings was found to be 15 %.

KOKKUVÕTE

PVD pinnete kulumine silelõikestantsi templitel

Silelõikestantsimine on eriomaste teadmiste ja oskustega stantsimismeetod, mis võimaldab toota kõrge lõikeserva kvaliteediga detaile, kus puhaslõige saavutatakse lisatöötluse vajaduseta ühe lõikeoperatsiooni tulemusena. Kõrge kvaliteedi eelduseks on tööriistade ja nende seadistuse suur täpsus. Silelõikestantsimise eripäraks võrreldes tavastantsimisega on väike õhupilu (0.5 % stantsitava materjali paksusest) ning vastusurve ja ringsaki (või ringsakkide) kasutamine lisaks lõikejõule. Nimetatud eriomased tunnused tagavad detaili tasapindsuse ning lõikeserva kvaliteedi. Tööriista lõikeservade ümbruses esinevad äärmiselt suured kontaktpinged, tuues kaasa tööriisa kiire kulumise. Kulumisega kaasneb suurenenud hooldusvajadus ning sagedased tööseisakud, kergitades seeläbi töö maksumust. Sageli on hoolduse põhjuseks just lõiketemplite kulumine. Eelnevad uurimustööd on näidanud, et füüsikalise aurustussadestuse meetodil (PVD) valmistatud kõvapinded võimaldavad märgatavalt tõsta tööriistade eluiga. Sellest tulenevalt on uurimistöö suunatud pinde kulumismehhanismi välja selgitamisele silelõikestantsimisel ning kulumiskindluse tõstmisele, kasutades erinevaid PVD pindeid, mida on võimalik toota Tallinna Tehnikaülikooli pindamislaboris.

Tööstuslikud katsed on oluliseks meetodiks pinnete tegeliku kulumiskindluse hindamiseks. Samas on nad keerukad, kuna tulemust mõjutavate faktorite hulk on küllaltki suur. Teatud kontrolli saavutamiseks tööstuskatsetustel arendati välja tööstuskatsetuste metoodika, mille eripäraks on, et pinnete kulumiskindluse hindamiseks kasutati mitmerealist tööriista, korduskatseid ning kulunud alade teisendamist suhteliseks protsentuaalseks kulumiseks. Tänu metoodikas kasutatavate meetmete rakendamisele osutub võimalikuks võrrelda omavahel erinevatest katsetest saadud tulemusi ning välistada stantsitava materjali partiist või erinevatest operaatoritest tulenevad mõjud. Ühtlasi muudab korduskatsete teostamine saadavad tulemused usaldusväärsemaks, välistades üksikute katsete läbiviimisel saadud juhuslike tulemuste aluseks võtmise.

Väitekirja eksperimentaalses osas kasutati kulumismehhanismi välja selgitamiseks tööstuskatseid kombineerituna skaneeriva elektronmikroskoobi (SEM) uuringutega. Tööstuslikes katsetustes kasutati nii lihvitud kui ka abrasiivtöötlusega viimistletud templeid. Templite pinnatöötluse erinevus on seotud templite kuju keerukusega – teatud juhtudel ei ole templi külgpind lihvimise abil töödeldav. Kulumismehhanismi uuringud näitasid, et nii lihvitud kui ka abrasiivtöödeldud lõiketemplite kulumismehhanismiks on nii abrasiiv-, adhesioon- kui ka väsimuskulumine. Kõik kolm mehhanismi leiavad aset üheaegselt ning on mõjutatud teineteisest, kuid eri kulumisetappides on ülekaalus erinevad mehhanismid. Kulumise algetapis on domineerivaks abrasiivkulumine, millele järgneb adhesioon- ja väsimuskulumine, mis viib lõpuks templi kildumise või purunemiseni.

Lisaks kirjeldatud kulumismehhanismile märgati tööstuskatsetustel kasutatud abrasiivtöödeldud templitel pinde diskreetsete osakestena eemaldumist. Taolist kulumismehhanismi on ka varasemalt muudes allikates märgatud ja kirjeldatud. Energiadispersioonspektromeetria (EDX) ja SEM uuringutelt saadud tulemused kinnitasid, et diskreetne pinde eemaldumine on põhjustatud pinde ja alusmaterjali vahelisel piirpinnal olevatest abrasiivosakestest, mis on sattunud pinnale abrasiivtöötluse käigus. Pinde pragunemine saab alguse abrasiivosakesest ning pinne eemaldub diskreetsete osakestena. Kirjeldatud viisil tekkinud kulumiskahjustusi templi külgpinnal ei eemaldata templi terituse käigus ning kohati paljastunud templi alusmaterjalist saab sageli alguse taastatud templi adhesioonkulumine.

Kulumiskindluse seisukohalt on väga oluline templi pinna topograafia. Lihvimise teel valmistatud templite tööstuskatsetustel selgus, et suhteliselt kõrge keskmine pinnakaredus *Ra* on oluline õlituse tagamiseks. Liiga väikse *Ra* korral õlitus halvenes ning pinde kulumine suurenes märgatavalt.

Abrasiivkulumiskindlus on sõltuv pinde kõvadusest (H), seega on suur pinde kõvadus oluline abrasiivkulumiskindluse parandamiseks. Erinevate allikate andmetel on silelõikestantsimisel eelistatud madala elastsusmooduliga (E) kõvapinded. Lähtudes soovitustest valiti erinevate pinnete teoreetilise kulumiskindluse hindamiseks kirjandusest tuntud kõvaduse ja elastsusmooduli suhted (H/E, H^2/E ja H^3/E^2). Abrasiivtöötlusega viimistletud templite tööstuskatsetel leiti seos PVD pinnete keskmise kulumise ja H/E suhte vahel. Pinded, millel oli kõrgem H/E suhe, omasid tööstuskatsetel paremat keskmist kulumiskindlust. Suhete H^2/E ja H^3/E^2 ning pinnete keskmise kulumise vahel tööstuskatsetustel ei leitud otseseid seoseid. Liugehõõrdekatsetes määratud hõõrdetegur ja kulumiskiirus ei olnud seoses tööstuskatsete tulemustega. Seega antud uuringutes kasutatud kujul ei ole laboratoorsed liugehõõrdekatsed sobilikud pinde kulumiskindluse ennustamiseks silelõikestantsimise rakenduses.

Nanokomposiitsed pinded nACo ja nACRo olid tööstuskatsetel keskmiselt 15 % parema kulumiskindlusega võrreldes TiCN pindega. Teemantilaadne pealispinne (DLC2), mis oli kantud AlCrN aluspindele, oli tööstuskatsetuste käigus suures ulatuses templi pinnalt eemaldatud ning DLC-ga templid ei olnud suurema kulumiskindlusega.

Kokkuvõtlikult võiks öelda, et templite kulumine silelõikestantsimisel toimub mitme kulumismehhanismi koosmõjul, kusjuures erinevates tööetappides domineerib erinev mehhanism. Kõvapinnete valikul tuleks eelkõige lähtuda pinnete H/E suhtest – mida suurem on see väärtus, seda suurema kulumiskindlusega on pinne. Katsetatud pinnete puhul leiti 15 % erinevus eri koostise ja omadustega pinnete keskmiste kulumiskindluste vahel.

APPENDICES

Curriculum vitae

1. Personal data

Name	Liina Lind
Date and place of birth	12.03.1985, Tallinn, Estonia
E-mail address	liina.lind@gmail.com

2. Education

Educational institution	Graduation year	Education (field of study/degree)
Tallinn University of Technology (TUT)		Materials engineering / Doctoral study program
Aalto University School of Science and Technology, Nordic Hysitron Laboratory	Guest student 2011-2012	
TUT	2009	Materials engineering / Master's degree
TUT	2006	Product development and engineering / Bachelor's degree
Pirita High School of Economics	2003	Secondary education
Tallinn Tondiraba Secondary School	2000	Elementary education

3. Language competence/skills (fluent, average, basic skills)

Language	Level
Estonian	mother tongue
English	fluent
Finnish	average
Russian	basic skills

4. Professional Employment

Period	Organisation	Position
2012 - …	TUT, Faculty of Mechanical Engineering, Department of Materials Engineering, Chair of Materials Science	early-stage researcher
2009 - 2012	TUT, Department of Materials Engineering	teaching assistant
2008 - 2009	AS Tehas Metallist	constructor
2005 - 2008	TUT, Department of Materials Engineering	technician

5. Research activity

Duration	Project name	Project no.
2012-2014	Advanced thin hard coatings in tooling	AR12134
2012	Interdiciplinary research project "Technology and properties of duplex-coatings" Financed by doctoral school "Functional Materials and Technologies" (FMTDK) under ESF project 1.2.0401.09-0079	
2007-2008	Training and e-study system development for quality engineers in a polymer and composite materials area	IN7081
2006-2007	RePlast FinEst educational and development project of recycling of plastics (WEEE)	V353
2006-2009 (participant in 2006)	Production of ultrafine and nanostructured WC-Co hardmetals from recycled scrap	ETF6758

6. Main areas of scientific work / Current research topics

Area of scientific work: T155 Coatings and surface treatment
Current research topic: Advanced thin hard coatings in tooling AR12134

Elulookirjeldus

1. Isikuandmed

Ees- ja perekonnanimi	Liina Lind
Sünniaeg ja -koht	12.03.1985, Tallinn, Eesti
Kodakondsus	Eesti
E-posti aadress	liina.lind@gmail.com

2. Hariduskäik

Õppeasutus (nimetus lõpetamise ajal)	Lõpetamise aeg	Haridus (eriala/kraad)
Tallinna Tehnikaülikool (TTÜ)		Materjalitehnika / doktoriõpe
Aalto University School of Science and Technology, Nordic Hysitron Laboratory	Külalis-doktorant 2011-2012	
TTÜ	2009	Materjalitehnika / magistrikraad
TTÜ	2006	Tootearendus ja tootmistehnika / bakalaureusekraad
Pirita Majandusgümnaasium	2003	keskharidus
Tondiraba Keskkool	2000	põhiharidus

3. Keelteoskus (alg-, kesk- või kõrgtase)

Keel	Tase
eesti	emakeel
inglise	kõrgtase
soome	kesktase
vene	algtase

4. Teenistuskäik

Töötamise aeg	Tööandja	Ametikoht
2012 - …	TTÜ, mehaanikateaduskond, materjalitehnika instituut, materjaliõpetuse õppetool	nooremteadur
2009 - 2012	TTÜ, materjalitehnika instituut, materjaliõpetue õppetool	assistent
2008 - 2009	AS Tehas Metallist	konstruktor
2005 - 2008	TTÜ, materjalitehnika instituut	tehnik

5. Teadusprojektid

Kestus	Teema	Projekti nr
2012-2014	Kõrgtehnoloogiliste õhukeste pinnete rakendamine tööriistade kulumiskindluse tõstmisel	AR12134
2012	Interdistsiplinaarne uurimisprojekt "Duplekstribopinnete tehnoloogia ja omadused" Rahastatud TÜ ja TTÜ doktorikool "Funktsionaalsed materjalid ja tehnoloogiad" (FMTDK) ESF projekti 1.2.0401.09-0079 alt	
2007-2008	Täiendkoolitus ja e-õppe süsteemi väljaarendamine materjalitehnoloogidele ning kvaliteediinseneridele polümeer- ja komposiitmaterjalide valdkonnas	IN7081
2006-2007	RePlast FinEst koolitus- ja arendusprojekt plasti (EER) taaskasutamisest	V353
2006-2009 (osaleja 2006. a.)	WC-Co jäätmeist ülipeene- ja nanostruktuuriga kõvasulamite valmistamine	ETF6758

6. Uurimisteemad

T155 Pinded ja pinnatehnoloogia

PUBLICATIONS

Paper I **Lind, L**., Peetsalu, P., Põdra, P., Adoberg, E., Veinthal, R., Kulu, P. (2010). Description of punch wear mechanism during fine blanking process. *Proceedings of 7th International Conference of DAAAM Baltic Industrial Engineering*, 504 - 509.

7th International DAAAM Baltic Conference
"INDUSTRIAL ENGINEERING"
22-24 April 2010, Tallinn, Estonia

DESCRIPTION OF PUNCH WEAR MECHANISM DURING FINE BLANKING PROCESS

Liina Lind, Priidu Peetsalu, Priit Põdra, Eron Adoberg, Renno Veinthal, Priit Kulu

Abstract: *Fine blanking is used to produce details with demanding quality. The process enables to create precision parts with straight edges showing little or no die break and superior finishing. In order to achieve better quality die clearance is very small, usually around 0.5% of the material thickness [1]. Therefore the tool components are under high contact stress and they have to work in extreme wear conditions resulting in poor tool lifetime. It is possible to increase tool lifetime by using tool reinforcing technologies, the right oiling conditions and adjusting cutting speed. Initially the wear mechanism has to be determined. Current article presents a simplified case for punch tribological system meaning that the influence of opposite punch and the v-ring is not considered.*

Laboratory tests, such as Rockwell coating adhesion test, and industrial experiments have been conducted with different coating compositions and punch surface roughness. Industrially the punches were used in automotive applications in fine blanking of cold-rolled steel strip.

Current article divides wear mechanism of punch into three phases. In first phase abrasive wear is the main mechanism of wear resulting in reduced surface roughness of punch. Therefore lubrication deteriorates and adhesion between coating and sheet metal occurs in second phase. In third phase intensive adhesion between the punch substrate material and sheet metal takes place and intensive stress causes fatigue wear.

Key words: fine blanking, punch wear mechanism, thin hard coating, adhesion

1. INTRODUCTION

The expanding use of high strength steels in fine blanking has brought out a new challenge – tool resistance and lifetime is not satisfactory any more. Whereas the blanking material has a direct influence to wear and tool endurance [2-4] the need for alternative and more resistant tools is therefore a topical issue.

Wear models for description of frictional and wear processes in fine blanking have several inputs. One input for these models are mechanical, physical and chemical properties of the coatings, especially mechanical behavior of coatings as micro-tribological processes are mostly governed by the coating properties.

Young's modulus of the coating has a big influence on the stresses developing within the coating during contact and lower modulus can decrease the amount of tensile stresses and therefore potentially increase the life of the coating.

Brittleness as the resistance to crack development should be high in a coating. The H/E (hardness / elastic modulus) parameter may be used to predict the wear resistance of a coating, where higher H/E ratio generally corresponds to higher wear resistance [5].

Another input of wear models is the tribological conditions of surface, for example roughness and lubrication. With insufficient lubrication, strong adhesive wear of the punch will occur and tool life is decreased because the adhesion leads to alternating stresses in tool surface resulting in tool fatigue near the surface. Cracks develop, grow and unite and tool material breaks out.

2. EXPERIMENTAL AND MATERIALS

2.1. Method for evaluating the wear of punches

For evaluating wear 16 industrial punches with different surface roughness were used. Punches were made from Böhler steel S390. The heat treatment was carried out at OY Bodycote using a vacuum furnace and obtained hardness was 65 HRC.
The surface grinding treatment (after heat treatment) of the tip was varied, which resulted in different surface roughness H and M. In fig. 1 the un-coated punch is shown, the tip and grip of the punch are pointed out.

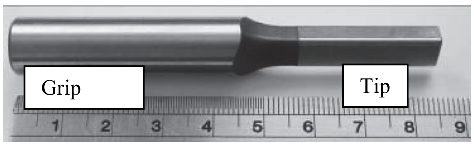

Fig. 1. Un-coated industrial punch

Two types of hard coatings were used on the punch tips – TiCN and AlCrN. TiCN coating was deposited without pre-treatment of the tool. With AlCrN micro blasting as surface preparation was used. The coating thickness was 1.4 µm with AlCrN and 3 µm with TiCN, measured using ball-cratering method Kalomax and microscope Zeiss Axiovert 25.
For evaluation of wear eight punches were used in production at the same time in fine blanking of 4.0 mm soft annealed sheet metal C60E. The punches analysed were located in eight different positions in two parallel lines. The state of stress in blanking material was somewhat different in each punch position due to the variations of deformation in the sheet metal. In order to diminish this effect the punches were distributed evenly on the layout.
For wear amount analysis the worn areas of all punches were measured with Omnimet Image Analyse System software along with stereomicroscope ZEISS Discovery V20. Punches with greater surface roughness, H, (table 3) had nearly two times smaller wear area. Results are shown in table 1.

Coating type	Area, mm^2
TiCN H	1.94
TiCN M	4.00
AlCrN H	2.15
AlCrN M	4.20

Table 1. Worn surface area of punches

2.2 Method for determining the coatings coefficient of friction

Coefficient of friction was determined with tribometer Wazau SVT500 using ball-on-disk method. The specimens were stationary and load was applied to the sliding ball. Steel ball was used in order to mimic the actual friction pare between punch and stamping material.
The tests were carried out with and without lubricant (the same oil which was used in industrial experiments) and the results are shown in table 2. Friction was found to be nearly 3 times smaller with all coatings when lubrication is used.

Coating type	Coefficient of friction	
	Dry	Lubricated
TiCN H	0.33± 0.04	0.10± 0.02
TiCN M	0.28± 0.04	0.10± 0.02
AlCrN H	0.34± 0.05	0.10± 0.02
AlCrN M	0.27± 0.03	0.12± 0.02

Table 2. Coefficient of friction between steel ball and coatings with and without lubrication

2.3 Method for determining the surface roughness of punches

For measuring the surface roughness Ra of punches a profilometer MAHR concept and contact method was used. The results are shown in Table 3.

Coating type	Marking	
	Rz	Ra
TiCN H	4.34	0.57
TiCN M	1.75	0.16
AlCr H	2.55	0.33
AlCr M	1.57	0.22

Table 3. Coating type and surface roughness (µm) of punches after coating deposition

2.4 Rockwell adhesion test

Rockwell adhesion test CEN/TS 1071-8 was used to study the adhesion between punch substrate and coating [6] and adhesion was determined according to 4 classes: "0"; "1"; "2" and "3". Where "0" is very good adhesion (no cracking or delamination of coating) and class "3" refers to the poorest adhesion (full delamination of the coating).

The results show that both studied coatings have similar adhesion, although in case of lower surface roughness (type M punch) somewhat better adhesion (class 1) was observed compared to class 2 in case of higher surface roughness (type H punch).

3. RESULTS AND DISCUSSIONS

The wear of the punch cutting edge leads to poor quality of blanked parts: formation of burr; shape distortion of detail surface caused by chipping of the tool cutting edge; cracking of cut surface [1].

The industrial punches used in current experiments are sharpened after 80 000 running cycles. The reason for regular maintenance is the wear of cutting edges and burr on cut surfaces.

The usual mechanisms for wear of punch are abrasive, adhesive and fatigue. These three mechanisms are related to each other and they often take place simultaneously however usually the wear is dominated by one mechanism. In different phases of the wear cycle the mechanism is not identical.

3.1 Abrasive wear

The amount of material removed by abrasive wear (V_{abr}) may be characterized by equation 1 [7].

$$V_{abr} = n^2 \frac{P_y E W^{\frac{3}{2}}}{K_{1C} H^{\frac{3}{2}}} L \qquad (1)$$

where E is elastic modulus, H is the hardness of the softer material, W is the normal load, L is the sliding distance, K_{1C} is the fracture toughness, n is the work-hardening factor and P_y is the yield strength.

3.2 Adhesive wear

Adhesive wear is influenced by the materials electronic structure, crystal structure and orientation, cohesive strength, hardness, melting temperature, oxide layers, lubrication conditions [7-8].

As a result of adhesion the material is separated from one surface and adhered on to the other causing uneven lubrication, higher contact stress and breakage of tools due to excessive grip [8-9].

Wear in lubricated friction pairs is different from dry wear conditions because the stress is partially transmitted to the lubricant. The main parameter characterizing the wear in lubricated friction pairs is the effective distance between surfaces λ (lambda ratio) which may be found with equation 2.

$$\lambda = \frac{h}{\sigma} \qquad (2)$$

where h is the lubricant thickness and σ is the square root of the surface variance (asperities) [7].

The value of λ will decrease when increasing stress and surface roughness or decreasing speed of movement or viscosity of lubricant.

If the lambda ratio is larger than 3 then metal to metal asperity contact is insignificant and adhesive wear is not possible. However if lambda is less than 1 then the operating regime is consider to be boundary lubrication and some adhesive and fatigue wear would be likely [7].

3.3 Fatigue wear

Fatigue wear is dependent of structure, cohesion strength, yield strength, residual stress and strength of material.

At the punch surface layer cyclic change of temperature occurs during fine blanking. Temperature of tool rises and compressive stress will form in the surface layer when sheet material is being cut, after which fast cooling is applied causing tensile stress.

Repeating this cycle fatigue cracks in the surface layer of punch are formed.

3.4 Experimental results and different phases of wear

Equation 1 indicates that surface roughness should not influence abrasive wear resistance. With respect to equation 2 the lambda ratio should decrease when Ra increases leading to larger contact stresses and temperatures. In fact temperature in the contact area could reach up to 800…900 °C [10]. Fatigue wear is favoured by poor adhesion between coating and punch.
However industrial experiments showed better wear resistance with higher surface roughness.
At the tip of the punch working conditions are most severe and contact with the blanking material is the longest. The tip initially starts the cutting of the sheet metal and is pulled out of the cutting zone last. Therefore the tip of the punch is worn the most (fig. 2).

Fig. 2. SEM photograph of punch cutting edge (after 80 000 cycles). Figure 3 will show a close-up of the worn surface indicated in the white box

On the basis of fig. 3 it is possible to divide the wear of punch into three zones. The tip (in left at fig. 3) of the punch has reached pre-breaking stage where all of the coating is removed, fatigue cracks are formed and intensive adhesion of sheet metal has taken place.
In the middle zone coating is preserved, however Ra is small and lubrication has become worse leading to adhesion (somewhat milder than in the first zone).
In the right side of fig. 3 coating is maintained and wear is modest.

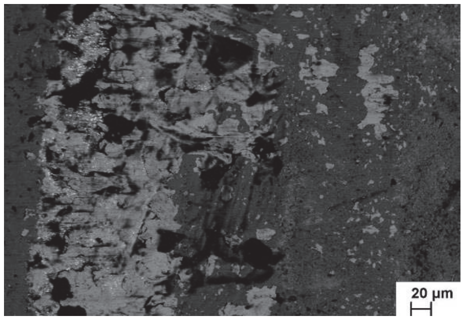

Fig. 3. The tip of the worn punch at greater magnification. The wear intensity is more intense at the tip (in the left)

The wear mechanism of fine blanking may be divided into three phases, where different wear types dominate.

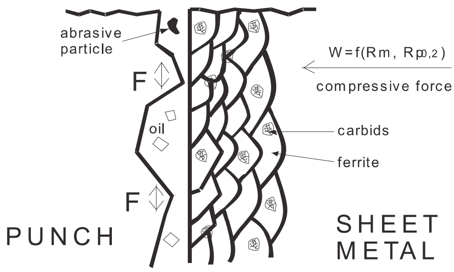

Fig. 4. Scheme of wear mechanism in the first phase

In the first phase the lubrication between the stamping material and the punch is sufficient and lambda ratio is situated somewhere between value 1 and 3. Partial contact between asperities of punch surface and sheet metal are taking place. Contact is not creating significant tensile stress, however stress would be higher when the strength properties Rm and Rp0.2 of sheet metal are increased thereby leading to severe wear.
Carbides and non-metallic inclusions of sheet metal and worn abrasive particles induce abrasive wear of the punch. In phase I the main mechanism of wear is abrasive due to good lubrication and few

contact asperities. Adhesion and fatigue are not significant in first phase of wear.

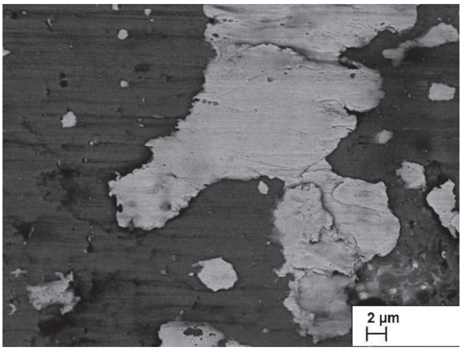

Fig. 4. Punch surface at second phase – many asperities of the surface have been "evened out" and consequently surface roughness has decreased

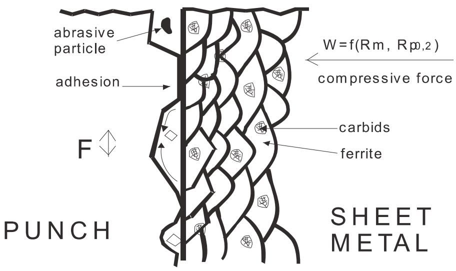

Fig. 5. Scheme of wear mechanism in the second phase

In second phase of wear lubrication conditions have changed due to decrease of coating roughness. Oil quantity between surfaces has decreased (λ is below 1).
Fig. 4 shows the SEM photograph of II phase and in fig. 5 the scheme for wear mechanism is brought. The adhesion of sheet metal to the punch is becoming dominant, which leads to greater stresses and higher contact temperature resulting from increased friction. In second phase the adhesion of coating to the punch substrate material, friction coefficient of punch and lubricants in oil become very important.
At the end of second phase the coating is fully removed from the punch revealing the substrate material (Böhler S390 steel) and as a result hardness, crystal structure and microstructure of the punch are changed. Intensive adhesion will appear even though surface roughness might increase.
In fig. 6 SEM photograph of wear in third phase can be seen and fig. 7 shows the scheme for III phase wear mechanism.

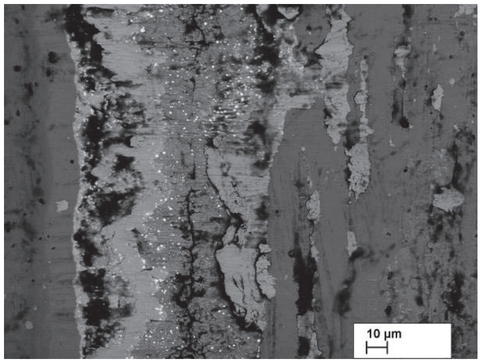

Fig. 6. Punch surface at third phase

During phase III the measurements of the punch may increase due to intensive adhesion. Therefore stresses and temperature might be elevated in the surface layer of the punch. The increase of force F might cause formation of a fatigue crack leading to chipping or breakage of the punch tip.

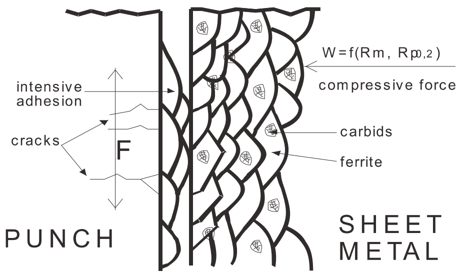

Fig. 7. Scheme of wear mechanism in the third phase

During fine blanking it is crucial to ensure the proper lubrication of surfaces and choose the proper surface roughness. However it is also important to prevent the amount of abrasive particles in sheet metal. For example wear can be decreased by using a stamping material with the same mechanical properties but with a lower carbon content and carbide amount.

4. CONCLUSIONS

The wear of punch in fine blanking is not connected to any specific wear mechanism therefore classical equations for evaluating wear can not be used.

Based on conducted experiments, the process of wear can be divided into three phases:

I – abrasive wear is dominant, adhesive wear is insignificant due to material asperities and lubrication between contact surfaces. Additionally adhesive wear is diminished by suitable crystal lattice structure and microstructure of the coating;

II – adhesion wear becomes dominant caused by the change in lubricating conditions. Wear becomes intensive;

III – the force and the stresses in fine blanking increase due to severe adhesion and change in punch measurements. Fatigue wear is becoming important and it may lead to cracking and breakage of the punch.

In order to improve the punch life-time it is important to avoid adhesive wear with the use of proper lubrication and decrease abrasive particles.

5. ACKNOWLEDGMENTS

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Paper II **Lind**, **L**., Adoberg, E., Aarik, L., Kulu, P., Veinthal, R., Alsayed, A.A.I. (2012). Tribological properties of PVD coatings with lubricating films. *Estonian Journal of Engineering*, 18(3), 193 - 201.

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Tribological properties of PVD coatings with lubricating films

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Abstract. This work reports on the tribological performance of three different commercial hard PVD coatings (TiN, TiCN and nACo) with lubricating extra films of Al_2O_3, Ni-WS_2 and diamond-like carbon (DLC). WC-Co hardmetal has been used as substrate material. Wear tests, employing two counter bodies of Al_2O_3 and hardmetal WC-Co, were performed for the PVD coatings with and without the extra films. The results showed that the presence of DLC extra film reduces the coefficient of friction of the PVD hard coatings TiN and nACo. Furthermore, the wear of TiN coatings was reduced in the presence of an extra Ni-WS_2 lubricant film.

Key words: PVD coating, thin film, tribology, self-lubrication, coefficient of friction.

1. INTRODUCTION

Physical vapour deposited (PVD) coatings have established a strong position in the tooling industry. Thin hard coatings are widely used to protect the tools from wear, to use substrate steels with higher toughness in cutting elements and altogether to extend tool life time. However, there are some limits related to the application of PVD coatings. For example, it has been demonstrated that multilayer and gradient coatings on hardmetal and cold work tool steel substrates under the conditions of dry sliding wear tests have a tendency to increase the coefficient of friction (CoF) and to decrease the elasticity modulus (E) and hardness (H) ratio [1].

Different types of hard coatings like TiN [2], Al_2O_3 (Alumina) [3], diamond-like carbon [4–6] and sulphide-containing films [6,7] can be applied for wear protection to lower the CoF or suppress the adhesive wear in poorly lubricated and high stress contacts. Previous studies have reported that hybrid PVD + atomic layer deposited (ALD) hard coatings have a positive effect on corrosion protection [8]. However, the effect of the ALD film on the wear resistance has not been studied to our knowledge.

The present study is part of an assignment to create thin hard coating systems for tooling industry in order to improve the commercial coatings known today. In this work, thin lubricating extra films were deposited on top of PVD coated surfaces. The influence of the extra films on the CoF and wear was studied.

2. EXPERIMENTAL

WC-Co hardmetal (10 wt% of Co) specimens with hardness of 1640 HV were used as substrate materials for the base coatings. Three base coatings, all containing elements of Ti and N, were used in the study – monolayer of TiN, gradient coating TiCN and gradient nanocomposite nACo (nc-$Ti_{1-x}Al_xN$)/(a-Si_3N_4). Substrate specimens were polished to Ra 0.003 μm and cleaned in an ultrasonic bath with isopropanol. Immediately after the cleaning procedure, samples were placed into the vacuum chamber and sputter-cleaned in argon plasma. Thin metallic Ti layer was deposited onto substrates prior to the main coating. Deposition of TiN, TiCN and nACo coatings were carried out in the arc plating PVD unit PLATIT-π80 using Lateral Rotating ARC-Cathodes (LARC) technology. The deposition temperature was 450 ºC for each coating. Thickness of the coatings was measured using the kalotest method with the kaloMAX tester. Surface roughness was measured with Perthometer Concept M by Mahr and nanohardness was received from Platit [9]. Properties of base coatings are given in Table 1. Adhesion of the coatings was evaluated by Rockwell indentation test (A scale), according to technical specification CEN/TS 1071-8.

Extra films used in the experiment were atomic film of Al_2O_3, sub-micron diamond-like carbon film and a micrometer thick nickel and tungsten disulphide composite film (Ni-WS_2).

Al_2O_3 film was deposited in a flow-type low-pressure ALD reactor [10] in a flow of nitrogen (99.999%, AS AGA). Prior to deposition, the samples were pretreated with acetone (99.5%, Carl Roth GmbH&CO) and isopropyl alcohol

Table 1. Properties of PVD base coatings

	Nanohardness, up to, GPa [9]	Average roughness Ra, μm	Average max height of the profile Rz, μm	Coating thickness, μm
TiN	24	0.04	0.91	2.5
TiCN	32	0.04	0.95	3.1
nACo	40	0.08	1.26	2.3

(99.7%, Carl Roth GmbH&CO). For preparation of reference samples, Al_2O_3 films were deposited also on Si substrates. The Si(100) substrates were cleaned by etching in HF to remove the native oxide, and then rinsed in de-ionized water. The Al_2O_3 film was deposited using 400 cycles $Al(CH_3)_3$ (98%, Strem Chemicals) and H_2O at 300 °C with the ALD cycle times 3/2/2/5 s. Mass thickness of Al_2O_3 films, grown by the ALD method on Si(100) substrates, was determined using EPMA data and STRATA and FLA programs [11].

Deposition of diamond-like carbon films was carried out in the PVD unit PLATIT-π80 using LARC technology at the temperature of 400 ºC. Recipe parameters were set according to recommendations from Platit in order to achieve film thickness of approximately 300 nm.

For the deposition of Ni-WS_2 composite coatings, an eutectic mixture of choline chloride and ethylene glycol, containing $NiCl_2$ and WS_2 powder, was employed. Electrodeposition experiments were carried out in open air conditions, using a three-electrode cell setup. During deposition process, the bath was stirred by a magnetic stirrer (10 rpm) in order to keep the particles dispersed and prevent sedimentation. Composite coatings were deposited at potential –0.9 V and temperature 70 ºC. After deposition, samples were rinsed with iso-propanol to ensure removal of the ionic liquid, and subsequently dried under vacuum at room temperature for 2 hours. The gravimetric method (weight gain) was used to calculate the coating thickness.

Reciprocating wear experiments were conducted using CETR-UMT-2 tribometer. Tests were carried out with two different counter bodies (supplied by Redhill): corundum (Al_2O_3) and tungsten carbide-cobalt (WC-Co) with 6 wt% of cobalt. Hardness and modulus of elasticity of Al_2O_3 was 1700 HV and 350 MPa, respectively; and for WC-Co 1500 HV and 640 MPa, respectively. Diameter of the ball was 3 mm, reciprocating distance 1 mm, contact force 2 N, frequency 5 Hz and time 10 min. All of the experiments were repeated at least twice and additional experiments were conducted for those samples where differences in the first two results were observed. Average CoF was determined over the period of 1500–3000 cycles, i.e. after stabilization depths of wear scars were determined using Bruker ContourGT-K0X White Light Interferometric Optical Profiler.

3. RESULTS AND DISCUSSION

3.1. Adhesion of PVD coatings and thickness of additional films

Adhesion between base coatings and the substrates was determined with Rockwell indentation test. Adhesion was very good – Class 0 (no cracks or adhesive delamination within the indent region) for nACo, or good – Class 1 (cracking without adhesive delamination of the coating) for TiN and TiCN coatings. Table 1 shows the thickness of PVD coatings of TiN, TiCN and nACo. The thickness of extra films was the following: Al_2O_3 – 0.04 μm, DLC – 0.3 μm and Ni-WS_2 – 1.0 μm.

3.2. Reciprocating sliding wear of different coating systems

Among the base coatings, TiCN demonstrated the best wear resistance in the specific conditions. TiN and nACo coatings were most susceptible to wear. Repeating the experiments with both counter bodies revealed some differences derived from the material of the counter body.

3.2.1. Effect of the counter body material on the CoF of base coatings

Wear behaviour of base coatings was studied using Al_2O_3 and WC-Co counter bodies. CoF dependence on the sliding ball material is shown in Fig. 1. Both of the nACo and TiN coatings showed more stable behaviour and lower CoF with WC-Co counter body. With nACo base coating Al_2O_3 counter body demonstrated remarkably higher CoF and wear depth, probably due to higher hardness of Al_2O_3. SEM secondary electron images of worn surfaces of nACo coating are presented in Fig. 2 and those with nACo + DLC coating in Fig. 3. With Al_2O_3 counter body (Fig. 2a), the wear is greater but the wear track is smoother. Larger contact pressure takes place with WC-Co (Fig. 2b) and the counter body is transferring and tearing the coating leaving a smaller wear track.

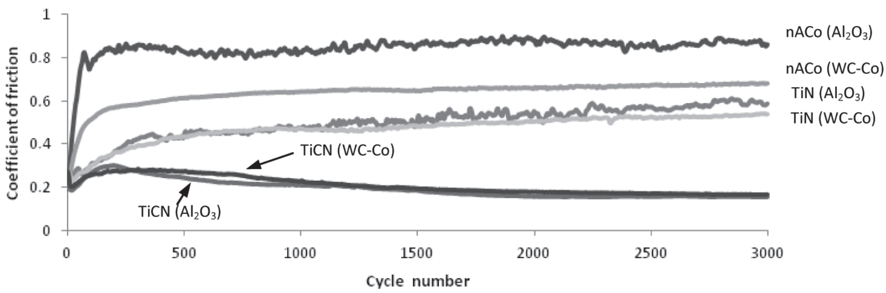

Fig. 1. Effect of the counter body material on the CoF of the base coatings.

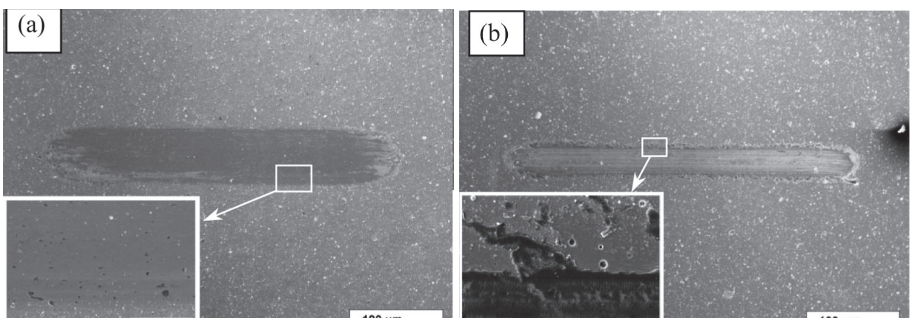

Fig. 2. SEM images of the nACo base coating, sliding against Al_2O_3 (a) and WC-Co (b) ball counterface.

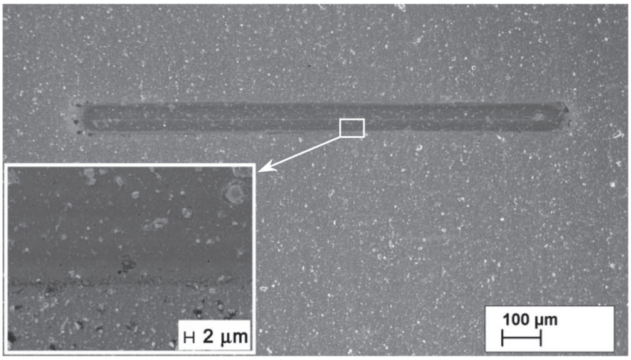

Fig. 3. SEM image of reciprocating wear experiment with nACo+DLC coating.

3.2.2. Effect of different extra films on CoF

It was observed that the presence of Al_2O_3 extra films on PVD coatings did not add tribological advantage to the PVD coatings (Fig. 4a). Some changes in the CoF during the "run-in" period are visible though for robust applications such influence will probably not be detectable. The effect of an ultra-thin extra film of Al_2O_3 disappears after the first 100 cycles and the CoF for the samples with the extra film levels off to the coefficient of PVD base coatings. Probably the extra film thickness is insufficient in order to provide protection to the base coating.

The presence of thin sub-micron DLC extra films on PVD coatings decreases the CoF and improves wear performance of the base coatings (Fig. 4b). On the basis of our experiment, it was noticed that the DLC film was able to provide remarkable protection to the substrate regardless of the base coating. Wearing out of the DLC coating was not noticed for any of the coating systems. SEM-secondary electron image of nACo+DLC is presented in Fig. 3. Wear track is remarkably smaller than for nACo coating without the extra film (Fig. 2).

Figure 4c represents the results for PVD coatings with Ni-WS_2 extra film (corundum counter body). For nACo+Ni-WS_2, CoF was lower up to 1000 cycles, however, afterwards the extra film failed and CoF reached the level of nACo base coating. The Ni-WS_2 extra film on TiN and TiCN was able to keep a reasonably stable low CoF up to 3000 cycles.

Sulphide-containing film of Ni+WS_2 was reliant on the base coating as it behaved differently for all three PVD coatings. The effect of Ni-WS_2 film on top of base coatings is presented in Fig. 5 where the wear behaviours of base coatings with and without the extra lubricant films are compared. The effect of the Ni-WS_2 film is remarkable for the TiN coating, while in case of the nACo coating, the effect depends on the counter body.

Table 2 shows an overview of the reciprocating wear experiment results and grouping of the wear behaviours. From the data, a relation between CoF and

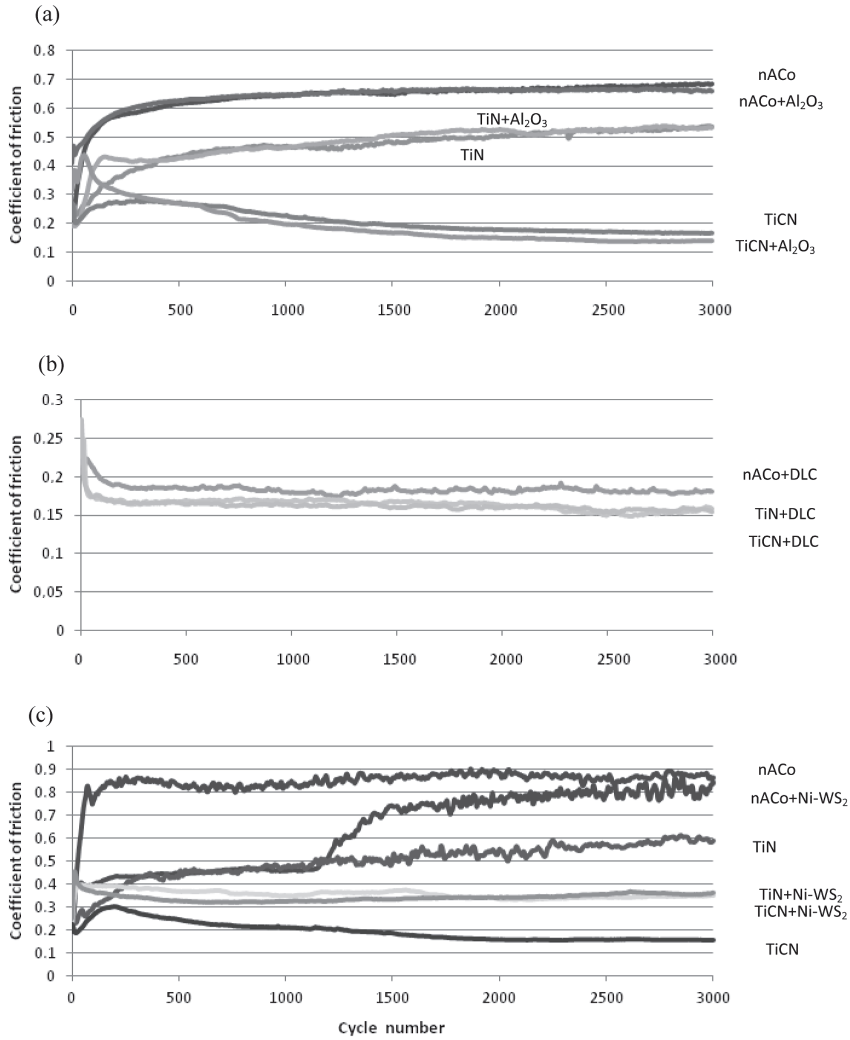

Fig. 4. Effect of extra films: (a) Al_2O_3 atomic film (sliding against WC-Co ball counterface); (b) DLC film (sliding against WC-Co ball counterface); (c) Ni-WS_2 film (sliding against Al_2O_3 ball counterface).

depth of the wear scar was noticed. Larger wear scars indicate a greater frictional coefficient. However, there were some exceptions. For the nACo coating systems (Table 2, group 4), depth of the wear scar was relatively deep, while the CoF remained low (0.4) with the hardmetal counter body. Ni-WS_2 in “group 2” coatings was able to suppress wear until the failure of the extra layer.

Table 2. Results of reciprocating wear tests with different PVD base coatings and extra films

Classification based on wear behaviour	Coating	Counterbody[1)]	Depth of wear scar, μm	CoF
Group 1: TiCN coating and DLC extra film on PVD base coatings. Low CoF and depth of wear scar.	TiN+DLC	WC-Co/Al_2O_3	0.10	0.16
	TiCN+DLC	WC-Co/Al_2O_3	0.13	0.16
	TiCN / TiCN+Al_2O_3	WC-Co/Al_2O_3	0.15	0.16
	nACo+DLC	WC-Co/Al_2O_3	0.14	0.18
Group 2: Ni-WS_2 extra film on base coatings. Increased CoF for TiCN and TiN but low wear. For nACo lower CoF for a short period is achieved, however, extra film wears out during the experiment.[2)]	TiCN+Ni-WS_2	WC-Co/Al_2O_3	0.05	0.35
	TiN+Ni-WS_2	WC-Co/Al_2O_3	0.11	0.35
	nACo+Ni-WS_2	Al_2O_3	0.95[2)]	0.45/0.78[2)]
Group 3: TiN coating. CoF is lower than for nACo, wear is high.	TiN / TiN+Al_2O_3	WC-Co/Al_2O_3	0.77	0.54
Group 4: nACo, nACo+ Ni-WS_2 and nACo+Al_2O_3 coatings with hardmetal counter body. Although nACo has higher CoF compared to TiN coating, wear is lower.	nACo+Ni-WS_2	WC-Co	0.45	0.64
	nACo / nACo+Al_2O_3	WC-Co	0.40	0.66
Group 5: nACo / nACo+ Al_2O_3 with Al_2O_3. Highest CoF and wear.	nACo / nACo+Al_2O_3	Al_2O_3	1.65	0.84

[1)] WC-Co/Al_2O_3 – no difference in results with different counter bodies.
[2)] The Ni-WS_2 coating wears out after about1200 cycles and therefore two values of CoF are given: CoF over a period of 100–1100 cycles / CoF over a period of 1500–3000 cycles. Wear scar depth is given only after the end of experimental 3000 cycles.

4. CONCLUSIONS

The paper considers tribological properties (wear and coefficient of friction) of commercial PVD coatings with lubricating extra films of Al_2O_3, DLC and Ni-WS_2. From the study the following conclusions can be made.

1. TiCN coatings showed the lowest coefficient of friction (0.15–0.20) and wear independence of the counter body material or of the extra lubricant films.
2. Atomic layer deposited Al_2O_3 extra films on PVD coatings did not add tribological advantage to the base coatings, probably due to insufficient thickness of the film. Wear and CoF remained on the same level as for PVD

commercial coatings, only minor changes in the "run-in" period were noticed.

3. Addition of DLC extra film on top of the base coatings resulted in a reduced CoF (to the level of 0.16–0.18) and wear of commercial PVD coatings TiN and nACo.
4. Extra film of Ni-WS_2 was able to provide good protection against wear of TiN and TiCN coatings in our experimental conditions; behaviour on nACo base coating was dependent on the counter body material. Extra film Ni-WS_2 needs further studies before it is possible to make more profound conclusions. For example, it remains unclear whether the protective effect of Ni-WS_2 will be preserved under higher loads or different setups and what is the reason for different behaviour with varied counter bodies.

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Määrivate katetega füüsikaliste aurustussadestuspinnete triboloogilised omadused

Liina Lind, Eron Adoberg, Lauri Aarik, Priit Kulu, Renno Veinthal ja Alsayed Abdel Aal

Artikkel käsitleb isemäärivate katetega (Al_2O_3, DLC ja Ni-WS_2) kaetud tuntud õhukeste kõvapinnete (TiN, TiCN ning nACo) triboloogilisi omadusi. Alusmaterjalina on kasutatud WC-Co kõvasulamit. Kulumiskatsete alusel võrreldi isemäärivate katetega kaetud katsekehasid puhaste kõvapinnetega. Katsetused viidi läbi erinevast materjalist kuulidega (kõvasulam WC-Co ja alumiiniumoksiid Al_2O_3). Teemandilaadne (DLC) kate vähendas hõõrdetegurit TiN-i ja nACo kõvapinnete puhul ning Ni-WS_2 lisakate vähendas TiN-pinde kulumist.

Paper III **Lind**, **L.**, Peetsalu, P. Sergejev, F. Wear of different PVD coatings at industrial fine-blanking field tests. *Materials Science (Medžiagotyra)*, (accepted).

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Wear of Different PVD Coatings at Industrial Fine-blanking Field Tests

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Thin hard physical vapor deposited (PVD) coatings play significant role on wear performance of fine-blanking punches in the presence of extremely high contact stresses. Nevertheless it seems that in blanking or fine-blanking the coatings are selected based on coincidence, trial-error-method or latest trends. There is limited information about planning and conducting the fine-blanking industrial field tests and measuring the wear of different coatings. In the present study a set of fine-blanking punches and laboratory specimens were prepared with three coatings – TiCN, nACRo and nACo. As substrate material Böhler S390 Microclean high speed steel was used. Coating mechanical properties (modulus of elasticity and nanohardness) were measured and wear rate with alumina ball was determined using the reciprocating sliding test. Wear of coatings was measured from punches after industrial use. All of the tested coatings showed high variance of wear. However coatings nACo and nACRo have better average wear resistance in fine-blanking compared with the well-known TiCN. Industrial field tests show correlation to the ratio elastic strain to failure H/E.

Keywords: PVD coating, wear, fine-blanking, industrial field test

1. INTRODUCTION

During fine-blanking process contact stress around 3000 MPa and temperatures about 400 ºC may be generated in the front face of the punches [1] setting high demands for the hard coatings and tools. Therefore PVD coatings with optimized properties are required. Previous studies have reported that from mechanical properties point-of-view low modulus of elasticity of coatings is desired accompanied with high hardness [2-5] providing good wear resistance and better performance. Foremost, coatings are expected to have low modulus of elasticity [6,7]. Multilayered structure of coatings is favoured since it provides resistance against crack development inside the coating and can decrease the modulus of elasticity [2,3].

The studies concerning fine-blanking are quite often based on theoretical hypothesis, analytical studies or FEM modelling which are verified through industrial tests. However, information regarding industrial test planning, setup and results analysis are not always thoroughly described. For example, there are studies reporting results achieved from industrial field tests concerning blanking [8] or fine-blanking [9] stating that certain coatings have advantages against the others; however data regarding the compared coating thickness, coating adhesion or tools specification is not discussed in depth. Straffelini *et al.* [5] have presented an interesting study about the shaving step in fine-blanking involving punches with different preparation techniques, nevertheless effect of different PVD coatings are not discussed. Furthermore, Klocke *et al.* [2] reports using TiN and TiAlN for fine-blanking punches without lubrication, however the focus of the study is on lubricants and different coatings for fine-blanking are not compared based on their lifetime.

For assessing coating performance it is important to test the coatings in a tribological system which is as close to the application as possible. The present paper is a development of an industrial field test to describe wear resistance of different coatings on fine-blanking punches. The developed industrial field test is used to demonstrate the performance of three different PVD coatings using the six-row fine-blanking tool. The planning and conducting of the field tests together with measuring wear of different coatings is presented. The proposed method has been partially employed in our previous studies [10,11] however the technique has been improved since then, and this is the first time the industrial field test method will be described in full extent.

2. EXPERIMENTAL DETAILS

2.1 Laboratory specimen preparation

Coatings were deposited on polished (Ra = 0.004 μm) specimens from hardmetal WC-Co (10 wt.% Co) and Böhler P/M S390 Microclean high speed steel (HSS) with hardness 65 HRC. Hardmetal substrates were used for determination of modulus of elasticity (E) and nanohardness (H) of the coatings. High E and H of the hardmetal are beneficial in avoiding substrate deformation during instrumented indentation.

2.2 Industrial tools preparation

Fine-blanking punches were manufactured from Böhler P/M S390 Microclean HSS, heat treated and annealed to hardness 64 HRC. Punches were wire-cut to shape using electric discharge machining (EDM). The “white layer” formed during EDM was removed by manual microblasting of the punches. Achieved surface roughness Ra for the punches was 0.6-0.9 μm.

2.3 Coating deposition procedure

Hard coatings TiCN, nACro ($AlCrN/Si_3N_4$) and nACo ($AlTiN/Si_3N_4$) were deposited using PVD equipment Platit π80 with Lateral Rotating ARC-Cathode technology. Prior to deposition laboratory specimens and industrial punches

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were cleaned in ultrasonic bath with isopropanol. Immediately after the cleaning procedure objects were placed into the vacuum chamber and sputter-cleaned in argon plasma. The deposition temperature was in the range of 450ºC for each coating.

2.4 Coating characterization

Nanohardness and modulus of elasticity (see Table 1) were measured from coatings deposited onto polished WC-Co substrates using MTS Nano Indenter XP. Indentations were done with a new Berkovich indenter using loads of 20, 30 and 50 mN in series of minimum 20 qualified measurements. Modulus of elasticity was calculated according to Oliver-Pharr [12] and CEN/TS [13] procedure.

Rockwell indentation method [14,15] was used to evaluate coatings adhesion (see Table 1) on polished HSS substrates. Coating thicknesses (Table 1) were measured from the same specimens using the ball-cratering equipment Kalotester KaloMax.

Wear rate of coatings on polished HSS substrates was determined using standard method [16] with the universal tribometer CETR UMT-2 and alumina ball, which enables to characterize the coating wear behavior in abrasive situation [17]. The experiments were carried out at room temperature and relative humidity of 55%. Reciprocating sliding mode was used with alumina counter body with diameter of 10 mm, contact load of 9.81 N, reciprocating distance of 2 mm and sliding frequency of 5 Hz (average speed 20 mm/s). Hertzian initial point mean contact pressure was 1.5-2 GPa dependent on the coating. Testing time varied from 5 to 10 minutes due to great differences between wear rates of different coatings. The testing time was shortened to 5 minutes for the nACo coating to avoid wear through the coating and the time was 10 minutes for TiCN and nACRo to achieve a measurable wear track. Depths of the wear tracks were measured using a 3D optical surface profilometer ContourGT-I from Bruker. Wear tests were repeated 3 times. Wear rate of coatings is presented in Table 1.

2.5 Industrial field tests

The tests were carried out in a 6 row progressive type tool with the hydraulic fine-blanking press HFA 4500 *plus* from Feintool and the steel strip material was S420MC with nominal thickness of 2.4 mm and tensile strength 550±70 MPa. Coatings TiCN, nACRo and nACo were applied on a set of 6 cutting punches i.e. 2 punches per coating. The set of punches was working at the same time. A special fine-blanking lubricant was used supplied by W.L. TriboTechnik.

The experimental fine-blanking punches were complex-shaped. The exact shape is confidential information. However the outline consisted of a flat line, and two different curvatures presented in Fig. 1-a. The size of the face of the punches could be fitted into a 10x15 mm size rectangle. Height of the punches varied from 70-90 mm depending on the number of times the punch was used i.e. after each test the tools are reconditioned by grinding off the tip of the punch. Nevertheless, the set of punches had the same height at all tests because they were reconditioned uniformly.

Side view of the punch is presented in Figure 1-b, which is in sliding contact with the steel strip during fine-blanking. Cutting edge of the punch is subjected to wear and during reconditioning it is removed. Worn area of the coating was considered to be equal to the surface area of revealed substrate of the punch (coating failed area). The measurement location and gauge i.e. the length of the wear measurement was always constant following the cutting edge of the punch. The gauge was chosen to be 5.7 mm. Figure 1-b presents the scheme of worn area measurement. Sometimes the punch exhibits areas of small discrete coating detachment, which are not always visible with optical microscopy (at Fig. 1 the areas are exaggerated in size). However these areas are excluded from the worn area calculation. The worn punches were photographed using the stereomicroscope ZEISS Discovery V20 and the worn areas were measured with OmniMet image analysis software from Buehler.

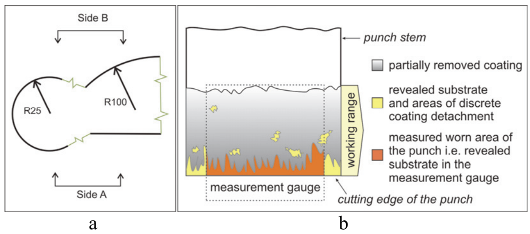

Fig. 1. Fraction of the face of the selected punch with representative side A and B, radius R is given in mm (a) and scheme of the coating wear measurement (b)

3. RESULTS AND DISCUSSION

3.1 Prediction of wear of the PVD coatings

PVD coatings are of significant importance at fine-blanking. To achieve better wear resistance constant development of the coatings is done. However for that understanding the connections between coating properties and wear resistance during fine-blanking is of key importance. The practical applicability of the PVD coatings is dependent on the order of magnitude of their main mechanical properties, such as hardness (H), modulus of elasticity (E), not only showing the coatings characteristics, but allowing to assess and compare coatings wear resistance on the basis of hardness to elastic modulus ratios. The hardness to elastic modulus ratios can be used to describe not only "elastic", but the "plastic" behaviour of the coating.

Previously published work of Leyland [6] describes the importance of the hardness to elastic modulus ratio and the effect of the higher ratios on the wear resistance of the coatings, allowing to conclude that the higher H/E ratio of the coating leads to reduction in wear, assumed that hardness is sufficently high. The elastic modulus should be adjusted to closely match that of the underlying substrate material, thus minimasing coating/substrate interfacial stress discontinuities under an applied load, allowing the coating to deform together with the substrate without cracking or debonding. Leyland calls the H/E ratio as elastic strain to failure.

Table 1. Properties of the PVD coatings

Coating	Coating type	Modulus of elasticity, GPa	Nanohardness, GPa	Coating thickness, μm	Adhesion class	Wear rate, 10^{-6} mm^3/Nm
TiCN	gradient	494 ± 24	31.9 ± 1.4	3.5	HF2	0,25
nACRo	gradient (nanocomposite)	429 ± 16	29.3 ± 0.6	3.3	HF3	0,22
nACo	multilayer (nanocomposite)	367 ± 8	25.3 ± 1.9	2.5	HF3	7,59

In the work of Musil it has been proved that the H/E ratio can be related to the elastic recovery *We*, the elastic energy for deformation, showing that coating with different hardness can exhibit same elastic recovery, providing approximately constant H/E ratios for different coatings [18]. This is why the different hardness to elastic modulus ratios should be used for better coating characterization.

The resistance to plastic indentation in the form of H/E^2 is a measure of the materials resistance to plastic penetration, and expected to correlate better with resistance to abrasive and erosive wear than either the hardness or the elastic modulus separately [19]. The high H/E^2 ratio is the indication of the material's better ability to resist permanent damage. As this mechanical property is only related to the contact area between two bodies, like blanking tool (punch) and workpiece (sheet metal), the higher the ratio is the higher load can be sustained without plastic deformation. The ratio H/E^2 allows as to compare coatings ability to resist local plastic deformation caused by abrasive particles at the punch and sheet metal interface.

Tsui *et al.* [20] describes the H^3/E^2 ratio as resistance to plastic deformation and as the best measure to correlate the mechanical properties to wear resistance of the hard coatings. Higher resistance to plastic deformation ratio means higher ability of coating to dissipate energy due to plastic deformation during loading.

The studied TiCN, nACo and nACRo thin hard coatings hardness to elastic modulus ratios, shown in Fig. 2, should not be analysed alone; e.g. in the case of H/E ratio the dimentional dissimilarity between coatings is too small for comparison. The measure of the resistance to plastic indentation H/E^2 provides distinguished comparison of the coatings, and leads to conclusion that nACo coating has the tendency to higher abrasive and erosive wear resistance among studied coatings. However the resistance to plastic deformation (H^3/E^2) of nACo coating is lowest, if compared with TiCN and nACRo coatings. If all three ratios are taken into consideration the nACRo coating seems to be the most promising candidate for highest performance in the conditions of intensive abrasion and erosion wear.

Another commonly known test to describe the coating properties is the reciprocating sliding test. The results of coating wear rate, see Table 1, are confirming the suitability of hardness to elastic modulus ratios concept to characterise the wear properties of the coatings. Coating wear rates (Table 1) show that nACo was far most susceptive to wear during dry reciprocating sliding, while nACRo and TiCN demonstrate relatively low wear. However, the wear rate with alumina is in great disagreement with wear ratios H/E and H/E^2 indicating that nACo should have better wear resistance than TiCN or nACRo (Fig. 2). The reason for this could be the nACo has lowest hardness. Wear rate from reciprocating sliding test is in good agreement with resistance to plastic deformation (H^3/E^2) ratios (see Fig. 2). This indicates that applied contact pressure at the reciprocating sliding test has probably exceeded the elastic deformation limit of the nACo coating at the largest extent.

In conclusion, nACRo seems to be advantageous considering to the superior relations of the hardness to elastic modulus.

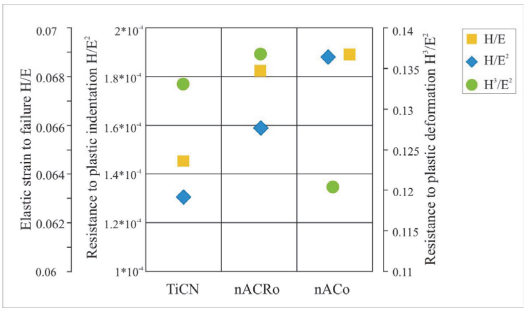

Fig. 2. Characteristic ratios of the selected PVD coatings

3.2 Selection of the tool for the industrial field tests

Lifetime of the tool is commonly assessed by the number of strokes made before defects appear on the product caused by wear, chipping or fracture of the tools. To find suitable tools for testing PVD coatings an analysis concerning production of 4 different components over a 2 year period was carried out based on the database records. The average number of strokes and the main failure reasons for the selected components were studied.

For testing the coating wear resistance it is preferred to have tools where the failure is commonly associated with formation of burr. Burr arises on the component when the clearance between the punch and the die exceeds the set value i.e. circumference of the punch cutting edge decreases or of the die increases. One of the main reasons for increase in the clearance is wear of the punch. Therefore for the industrial field test a tool was selected where the probability of burr was 38% and chipping 13%, the average number of strokes between maintenance was 8600. All statistics are given over a 2 year period.

3.3 Assurance of the same working conditions of different coatings during the industrial field tests

PVD coating wear resistance measurements in the field are essential to understand coating behaviour in its application. Measuring the wear resistance of the different coatings it is critical to assure same working conditions for all coatings. At the industrial scale there are many variables which are difficult to control, e.g. variations between different batches of the sheet metal, positioning accuracy (assembly), lubrication conditions and the tool operator. We have employed following means to ensure that testing of different coatings in industrial situation is conducted under comparable conditions:

- The heat treatment, EDM, micro-blasting and handling was alike for the set of 6 test punches.
- A 6-row progressive tool enables using six punches which are working at the same time in similar conditions. Wear is converted into relative percentage (see chapter 3.4). This measure excludes possible variations in sheet metal batch, press type, factory temperature and the operator. Furthermore, having 6 punches in the tool allowed us to test three different coatings and to have two punches per each coating.
- Repetitive tests were conducted. One single test may give misleading results. Furthermore, fully coated punches may behave differently than the reconditioned ones i.e. tip of the punch is left uncoated after reconditioning. In ideal coatings should have good lifetime with both occasions.
- Rearranging the punches with different coatings in between repetitive tests. Variations in wear might be caused by specific rows therefore it's necessary to rearrange the punches.

3.4 Industrial field tests

Because of the complex shape of the selected punch it was required to consider several places for coating wear measurement (Fig. 3 and Fig. 1). Light from the microscope was able to illuminate the flat side A without formation of shadows and focusing was easy. However it was found that side A was less affected by wear when compared to side B (Fig. 3). Variations between wear of different coatings were not detectable from side A. Furthermore two magnifications were considered, mag. 15x enabled clearer

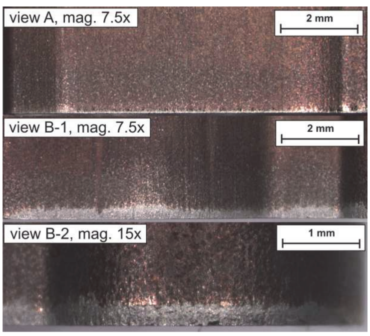

Fig. 3. Industrial worn punch coated with TiCN. The topmost view A is from side A and views B-1 and B-2 represent side B, radius 100 mm and 25 mm respectively.

vision of wear boundary. However the curvature of the punch in view B-2 was too great to enable focusing the entire surface and also it was better to include a larger area because of the possible variations in wear height along the cutting edge. In conclusion, view B-1 with magnification 7.5x was selected for analysis and all the following results are based on wear measured from that view.

Between repetitive tests worn areas of the PVD coatings should not be directly compared and averaged since the number of strokes varied from 20 500 to 45 000. To enable comparing results worn areas were converted into relative wear percentage. For each test the most worn punch with area a_{max} was determined and referred to as 100% wear. With the repetitive experiments it was revealed that in row 1 (R1) wear was always almost two times higher (see Fig. 4). Therefore a_{max} is determined from rows 2-6 excluding R1. Relative wear of the coating w_i was calculated according to Eq. (1), where a_i is the worn area of the punch in row i (i =2-6).

$$w_i = \frac{a_i \cdot 100}{a_{max}} \qquad (1)$$

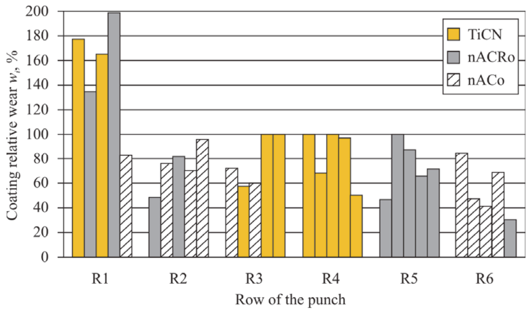

Fig. 4. Wear results throughout the 5 field tests. For each row 5 columns is given representing the test no. 1 - 5 from left to right, respectively.

Figure 4 presents the relative wear data as raw data from 5 repetitive industrial field tests made with a six-row (R1-R6) tool. Each repetitive test consists of results from six punches with three coatings. Coatings are shown in Figure 4 with different colour and pattern scheme. Coated punches are rearranged in between the repetitive trials to achieve reliable results and that is the reason why each row (R) consists of different coating columns. At field test no. 5 the wear in R1 is comparable with other rows. Reason for this is likely connected to the changed guide plate. Further analysis neglects results from R1 concerning field tests 1-4 since increased wear at these tests in that specific row is most likely caused by the tool setup or design and not strictly related to the coating composition or properties.

The quantitative analysis of the data in Figure 4 is given in Figure 5 in the form of the average, median and upper-lower limits of wear for the tested coatings. Average and median value of the well-known TiCN coating shows highest wear however it is difficult to differentiate nanocomposite nACRo from nACo. The nACRo coating showed unstable behaviour by having excellent wear resistance at some tests while being the poorest at other tests. TiCN can also be good at some tests however using only the TiCN coatings at the production would probably result in decrease of the overall punch lifetime compared with nACRo or nACo.

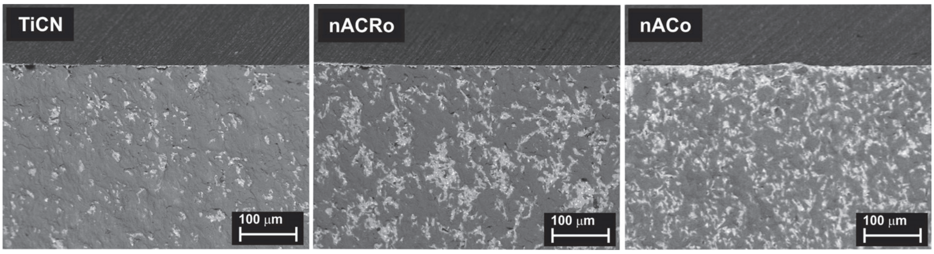

Fig. 6. SEM of punches after the reconditioning procedure.

From Figure 5 it could be estimated that the difference between average wear of the coatings is 14-17%. Comparing only the minimum relative wear values of coatings the difference between the best (nACRo) and worst (TiCN) punch is somewhat higher reaching 19%. However comparing only the maximum relative wear values the difference between nACo (best) and TiCN (worst) is only 5 %.

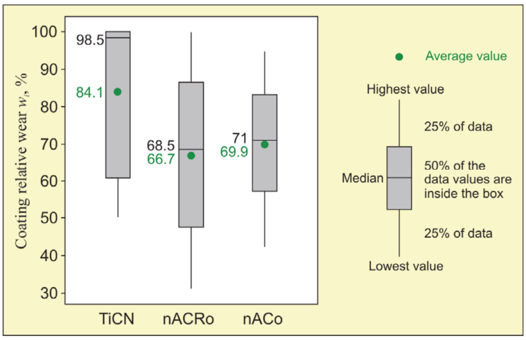

Fig. 5. Relative wear of coatings at repetitive industrial field tests.

Statistical analysis presented in Figure 5 shows high variation of the industrial tests and importance to have repetitive tests as one test could give misleading results even though the punches are working in similar conditions. Furthermore coating wear rate may change during its lifetime (which is approximately 10 reconditioning's).

In between the repetitive trials the tips of the punches are ground i.e. reconditioned. Aim of the reconditioning procedure is to remove the visibly worn areas of the punch cutting edge. However the sheet strip thickness (i.e. working range of the punch) is several times higher compared to the worn area height (see Fig. 1-b). Hence the reconditioned punch working range coincides with the working range at the previous operation. Therefore with reconditioned punches the coating close to the cutting edge is not new but already worn (Fig. 6).Since the reconditioning is done several times it is inevitable that reconditioned punch coating close to the cutting edge has already wear marks and therefore wear rate of the individual studied coatings can change. Coating showing good results in a new state may wear with increased rate at the reconditioned state.

The goal of industrial field test development is to get reliable information about coating behaviour in the actual tribological contact (at fine-blanking punch) and use the information to select and develop coatings. The industrial fine-blanking field tests show correlation to the ratio elastic strain to failure H/E (Fig. 2). Coatings nACo and nACRo show better resistance to the failure than TiCN. Accordingly it is not important to have high hardness of the coating but low elastic modulus (close to the substrate material) to keep the stresses inside coating low. There is no connection of the industrial field tests with the reciprocating sliding test with Al_2O_3 ball and also there is no direct connection to resistance to plastic indentation (H/E^2) and resistance to plastic deformation (H^3/E^2).

3.5 Industrial field test uncertainty

Relative wear of each coating varied between rows and different tests within a wide range (Fig. 5) extending from 50 % up to 70 % difference between upper and lower relative wear values. There could be many reasons for this dispersion. One reason could be positioning or wear of the punch guide plates. However in case of positioning errors one side of the punch would suffer from higher wear than the other. Yet, this was not the case since both sides of the punch were always checked and such positioning errors were not noticed. Most likely the high dispersion in results is connected to the punch preparation, i.e. EDM treatment and micro-blasting (pre-treatment) prior to the PVD coating process. Substrates of the punches were manually microblasted before the coating deposition. With manual blasting it is difficult to guarantee that the topography will be uniform. Moreover, impurities on the substrate i.e. particles from microblasting which are embedded into the surface may be the cause for cracking and detachment of discrete coating areas [21,22].

Future work should consider better control over the preparation of punches. Excluding coating adhesion variations derived from the EDM process or the following abrasive treatment needs increased attention. This includes removal of the "white layer", controlling the surface topography, efficient cleaning of the punch surface prior to PVD coating deposition.

4. CONCLUSIONS

A wear measuring method for industrial tools is proposed enabling comparing results obtained from different industrial field tests and eliminating factors, which are not always constant (e.g. number of strokes, steel batch). The technique is relatively simple however visible wear of the coatings and multiple row tool are required for using the method. The proposed industrial method has potential to be implemented with research involving influence of surface topography, coating thickness and also with different substrate materials to assess the wear performance. To decrease uncertainty of the industrial field tests great attention should be directed to preparation of the tools e.g. uniform removal of the white layer formed at the EDM treatment.

Industrial field tests with fine-blanking punches included three PVD coatings TiCN, AlCrN/Si_3N_4 (nACRo) and AlTiN/Si_3N_4 (nACo). Following conclusions were reached:

1. According to average coating wear values the TiCN coating showed estimately 15-17% higher wear than nACRo and nACo.
2. It is difficult to differentiate between nACRo and nACo where nACRo could have in some cases excellent wear resistance and it could be also most worn coating.
3. Industrial field test show correlation to the ratio elastic strain to failure H/E. It is important to keep the stress level inside the coating as low as possible using coatings with low modulus of elasticity, maintaining sufficient hardness to provide high wear resistance.
4. Reciprocating sliding test results, ratios H/E^2 and H^3/E^2 do not show correlation with the industrial field test results.

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