© Strojniški vestnik 50(2004)3,146-156
ISSN 0039-2480
UDK 621.7.016.3:621.793
531.4:539.62
Izvirni znanstveni članek (1.01)

© Journal of Mechanical Engineering 50(2004)3,146-156
ISSN 0039-2480
UDC 621.7.016.3:621.793
531.4:539.62
Original scientific paper (1.01)

Možnosti uporabe trdih prevlek na preoblikovalnih orodjih

Wear And Friction Properties Of Hard Coatings For Forming Tools

Bojan Podgornik - Sture Hogmark - Odd Sandberg

Namen predstavljenega prispevka je bil raziskati možnosti uporabe trdih prevlek fizikalno nanešenih v vakuumu (FNV - PVD) na orodjih za hladno preoblikovanje. V raziskavo so bile vključene prevleke TiN, TiB_2, TaC in diamantu podobna prevleka na podlagi trdega ogljika (DPP), katerih tribološke lastnosti smo primerjali z različnimi orodnimi jekli za delo v hladnem jeklarne Uddeholm Tooling iz Švedske. Tribološke lastnosti materialov, vključenih v raziskavo, smo določili na preizkuševališču, katerega izoblikovanost omogoča izmenično in zvezno povečevanje ter zmanjševanje obremenitve med drsenjem. Obremenitev je bila v območju med 100 in 1300 N (kontaktni tlak med 1 GPa in 5 GPa), kot protimaterial pa smo uporabili avstenitno jeklo.

Rezultati raziskave kažejo, da uporaba ustrezne prevleke privede do povečane obrabne obstojnosti orodja ter do precejšnjega zmanjšanja pojava lepljenja obdelovanega materiala na površino orodja.

(Ključne besede: preoblikovanje hladno, prevleke trde, adhezija, obraba, trenje)

The aim of this paper was to investigate the potential of using hard physical vapour deposition (PVD) coatings on forming tools. A tribological evaluation of TiN, TiB_2, TaC and diamond like coating (DLC) coatings deposited on cold-worked tool steel was carried out in a load-scanning test rig and compared to the behaviour of different uncoated forming tool steels. The special test configuration, where austenitic stainless steel was used as the counter-material, makes it possible to gradually increase the normal load during forward sliding strokes, and to correspondingly decrease the load during reversed ones. In this investigation, the load range was 100 to 1300 N (contact pressure from 1 to 5 GPa).

The experimental results indicate that the introduction of an appropriate hard coating will lead to an improved wear resistance and a longer lifetime for the forming tool. Furthermore, by using hard low-friction coatings excellent anti-sticking properties can be obtained.

(Keywords: cold forming, hard coatings, adhesion, wear, friction)

0 UVOD

V predelovalni industriji se trde zaščitne prevleke že vsakodnevno uporabljajo za povečanje obstojnosti in produktivnosti odrezovalnih orodij [1]. Zahteve po delu v agresivnih okoljih in vedno večje zahteve po oksidacijski ter obrabni obstojnosti orodij narekujejo nenehen razvoj na področju trdih zaščitnih prevlek [2]. Kljub vsemu pa v predelovalni industriji še vedno prevladuje prevleka TiN, ki je bila razvita že pred več kot dvema desetletjema.

V nasprotju z odrezovalnimi orodji je uporaba trdih prevlek pri preoblikovalnih orodjih še vedno redkost. Večina preoblikovalnih orodij je velikih izmer in zahtevne geometrijske oblike, kar otežuje nanos trdih prevlek ter doseganje ustrezne

0 INTRODUCTION

Hard and corrosion-resistant coatings are frequently used to protect and enhance the lifetimes of tools under high and constant wear loads [1]. Although introduced more than two decades ago, TiN still dominates among the hard coatings applied in industry. However, the requirements to withstand aggressive environments and to improve oxidation resistance and wear resistance under extreme conditions has led to the development and introduction of new coatings [2].

In contrast to cutting tools, the majority of forming tools is still uncoated. This is due to their larger size and the complex shape of most forming tools, which makes it difficult to apply a coating and to obtain good adhesion between the coating and the substrate material [3]. Although hard ceramic coatings are routinely oprijemljivosti le-teh [3]. Kljub temu, da tudi pri odrezovalnih orodjih luščenje prevleke ni zaželeno [4], to ni kritično. V primeru preoblikovalnih orodij lahko delci odluščene prevleke zaidejo v stik, s čimer poslabšajo kakovost izdelka, po drugi strani pa lahko privedejo tudi do kritične poškodbe izredno dragega orodja. Seveda obstajajo še drugi razlogi, zakaj se trde prevleke v preoblikovalni industriji ne uporabljajo bolj pogosto. Eden od najpomembnejših je razmeroma visok koeficient trenja komercialnih trdih keramičnih prevlek [1], ki povzroči lepljenje obdelovanega materiala na površino orodja [5]. V zadnjih nekaj letih pa je bil narejen izjemen napredek tako na področju nanašanja trdih prevlek, kakor tudi pri razvoju prevlek na osnovi trdega ogljika z izjemnimi tornimi lastnostmi ([6] do [9]).

Namen predstavljene raziskave je bil preučiti možnosti uporabe trdih prevlek, nanesenih z metodo fizikalnega nanašanja iz parne faze (FNV), na orodjih za hladno preoblikovanje. Obrabno in torno obnašanje prevlek TiN, TiB_2, TaC in DPP pri preoblikovanju avstenitnega jekla smo primerjali z lastnostmi orodnih jekel za delo v hladnem jeklarne Uddeholm Tooling iz Švedske.

1 EKSPERIMENTALNI DEL

V predstavljeno raziskavo so bile vključene prevleke TiN, TiB_2, TaC in prevleka na osnovi trdega ogljika (DPP), ki so bile nanesene na kaljeno in popuščeno orodno jeklo za delo v hladnem vanadis 4 (Uddeholm Tooling, Švedska), brušeno na $R_a \approx 0{,}2$ μm. Vse štiri prevleke, debeline 2 μm, so bile nanesene z uporabo komercialnih postopkov fizikalnega nanašanja iz parne faze (FNV). Parametri nanašanja in lastnosti uporabljenih prevlek so predstavljeni v preglednici 1. Prevleka DPP z večplastno strukturo volframovega karbida (WC) in amorfnega ogljika (a-C:H) je bila nanesena pri temperaturi podlage

deposited with excellent adhesion, there is always the risk of depositing a coating with poor adhesion [4]. Although this is very undesirable for cutting tools, it is not a disaster. However, if a coating fails on a forming tool, coating fragments can become a source of abrasive particles within the system, which can lead to poor surface quality of the product and the destruction of a very expensive tool. There are other reasons why normal hard coatings are not used more widely in forming-tool applications. One is the relatively high coefficient of friction generated by most of the commercial ceramic coatings used in cutting-tool applications [1], which leads to a high tendency to galling when sliding against soft metals [5]. However, in the last couple of years tremendous progress has been seen in the field of coating deposition as well as in introducing new carbon-based coatings with excellent frictional properties ([6] to [9]).

The aim of this study was to investigate the possibilities of using hard PVD (physical vapour deposition) coatings on forming tools. A tribological evaluation of TiN, TiB_2, TaC and DLC coatings deposited on cold-worked tool steel was carried out in a load-scanning test rig and compared to the behaviour of different uncoated forming-tool steels, using soft austenitic stainless steel as the counter material.

1 EXPERIMENTAL WORK

Four different PVD coatings – TiN, TiB_2, TaC and DLC – with a thickness of about 2 μm were used in this investigation. The investigated coatings were deposited on a hardened and tempered powder-metallurgy cold-worked tool steel, vanadis 4 (Uddeholm Tooling AB, Sweden), using commercial PVD processes. The process parameters and the properties of the coatings are listed in Table 1. The DLC coatings, which were WC-doped hydrogenated diamond-like carbon coatings with a multilayer structure of WC and amorphous carbon (a-C:H), were deposited at a substrate temperature of ~230°C. For the refractory hard coatings of TiN, TiB_2 and TaC, the deposition temperature was in the range between 70 and

Preglednica 1. *Parametri nanašanja in lastnosti raziskovanih prevlek*
Table 1. *Deposition parameters and resulting coating properties*

prevleka coating	postopek nanašanja deposition process	temperatura temperature [°C]	trdota hardness [GPa]	modul elastičnosti Young's modulus [GPa]	zaostale napetosti residual stress [GPa]
TiN	elektronski snop reactive e-beam	320 - 420	30±2	500±50	-3,8±0,4
TiB_2	napršEevanje sputtering	300	54±9	600±85	-0,5±0,2
TaC	napršEevanje sputtering	70	15±2	230±20	-1,1±0,2
DLC	reakcijsko napršEevanje reactive sputtering	230	12±1	130±7	-0,3±0,1

Preglednica 2. *Postopek izdelave in sestava uporabljenih orodnih jekel za delo v hladnem*
Table 2. *Production process and nominal chemical composition of the investigated forming tool steel*s

orodno jeklo steel	postopek izdelave* production process*	kemična sestava nominal chemical composition						
		%C	%Si	%Mn	%Cr	%Mo	%V	%W
VANADIS 4	MP	1,5	1,0	0,4	8,0	1,5	4,0	-
VANADIS 6	MP	2,1	1,0	0,4	6,8	1,5	5,4	-
VANADIS 23	MP	1,3	0,5	0,3	4,2	5,0	3,1	6,4
WEARTEC	TN	2,8	0,8	0,7	7,0	2,3	8,9	-

*MP – metalurgija prahov / powder metallurgy, TN – tehnologija naprševanja / spray forming

Preglednica 3. *Toplotna obdelava in trdota površine raziskovanih orodnih jekel za delo v hladnem*
Table 3. *Process, heat treatments and resulting hardness values of the investigated forming tool steels*

orodno jeklo steel		toplotna obdelava heat treatment	parametri toplotne obdelave treatment parameters	trdota hardness
VANADIS 4	AH	kaljenje hardening	1050°C/30min/air + 525°C/2x2h	62 HRC
VANADIS 4	AN	nitriranje v plazmi plasma nitriding	500°C/9h/95%H_2-5%N_2	1200 $HV_{0,1}$
VANADIS 6	B	kaljenje hardening	1050°C/30min/ air + 525°C/2x2h	62 HRC
VANADIS 23	C	kaljenje hardening	1050°C/30min/ air + 560°C/3x1h	62 HRC
WEARTEC	D	kaljenje hardening	1020°C/30min/ air + 525°C/2x2h	62 HRC

~230 °C, medtem ko so bile enoplastne prevleke TiN, TiB_2 in TaC nanesene v temperaturnem območju med 70 °C in 420 °C (preglednica 1). Za doseganje ustrezne oprijemljivosti prevlek so bile le-te nanesene na ~0,1 µm debelo vmesno plast titana (TiN, TiB_2 in TaC) ali kroma (DPP).

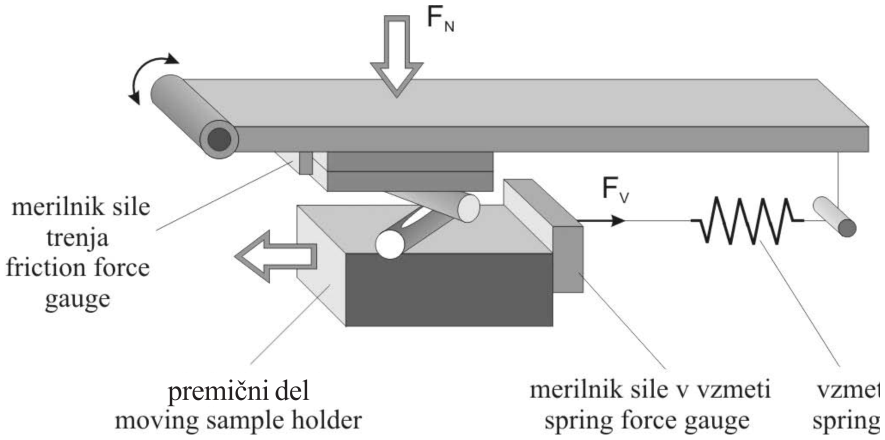
Tribološke lastnosti oplaščenega orodnega jekla vanadis 4 smo primerjali z lastnostmi neoplaščenega kaljenega ali nitriranega jekla vanadis 4 ter še s tremi orodnimi jekli za delo v hladnem jeklarne Uddeholm, predstavljenih v preglednicah 2 in 3. Kot protimaterial pa smo uporabili mehko žarjeno avstenitno jeklo AISI 304 (350 HV) ter kaljeno jeklo za kroglične ležaje AISI 52100 (850 HV).

Tribološki preizkusi so bili narejeni na napravi, katere izoblikovanje dveh cilindričnih preizkušancev s premerom 10 mm ($R_a \approx 0,2$ µm) omogoča izmenično in zvezno povečevanje ter zmanjševanje obremenitve med samim drsenjem ([10] in [11]), (sl. 1). Pri tem je vsaka točka vzdolž drsne poti pri obeh preizkušancih izpostavljena točno določeni obremenitvi. V predstavljeni raziskavi je bila obremenitev v območju med 100 in 1300 N, kar ustreza Hertzovemu stičnemu tlaku med 1 GPa in 5 GPa. Določitev tornih lastnosti in sposobnosti raziskovanih materialov preprečiti prenos ter lepljenje protimateriala (avstenitno jeklo) na površino

420°C. To improve the adhesion of the coatings, a thin (~ 0,1 µm) Ti intermediate layer was deposited for the TiN, TiB_2 and TaC coatings, and a Cr layer for the DLC coating, prior to the coating deposition.

The tribological properties of the coated vanadis 4 steel were investigated in the load-scanning test rig and compared to uncoated hardened or plasma nitrided vanadis 4 steel, as well as to three different forming-tool steels, produced at Uddeholm Tooling AB, see Table 2. The heat treatments and the hardness values of the forming-tool steels included in this investigation are given in Table 3. As a counter material in the load-scanning tests, a soft (350 HV) austenitic stainless steel (AISI 304) was used for the friction tests and a hardened and tempered (850 HV) ball-bearing steel (AISI 52100) for the wear-resistance assessment.

In the load-scanning test rig, which involves two crossed, elongated cylindrical test specimens of diameter 10 mm (Ra ≈ 0,2 µm) that are forced to slide against each other under a constant speed, the normal load is allowed to gradually increase during the forward stroke and to correspondingly decrease during the reverse stroke ([10] and [11]), Figure 1. Thus, each point along the contact path of both specimens will experience a unique load and display a unique tribological history after the completion of the test. For the purpose of this investigation the range of the normal load was of the order of 100 to 1300 N. However, depending on the tribological property investigated, a different mode of testing was used. For the purpose of anti-sticking tests, where the ability of the investigated materials and coatings



Sl. 1. *Shematični prikaz naprave za tribološko preizkušanje*
Fig. 1. *Load-scanning test rig*

orodja je potekalo v razmerah suhega drsenja, pri drsni hitrosti 0,01 m/s. Preizkus je bil končan, ko je obremenitev dosegla največjo vrednost 1300 N.

Za določitev tornih lastnosti raziskovanih prevlek in orodnih jekel za delo v hladnem proti mehko žarjenemu avstenitnemu jeklu smo uporabili ponavljajoče preizkušanje pri drsni hitrosti 0,1 m/s. Pred preizkusom je bila na površino preizkušancev nanesena tanka plast neaditiviranega poli-alfa-olefinskega olja (PAO; v_{40} = 46,6 mm^2/s) debeline ~10 µm.

Tudi obrabna obstojnost raziskovanih materialov je bila določena pri drsni hitrosti 0,1 m/s, pri čemer je bil protipreizkušanec, izdelan iz kaljenega jekla 100Cr6, potopljen v neaditivirano olje PAO. Obraba raziskovanih materialov v razmerah mejnega mazanja je bila določena z uporabo optične mikroskopije in profilometrije, in to po 200 ciklih izmeničnega drsenja, na točki izpostavljeni obremenitvi 700 N.

to prevent the transfer of a soft austenitic stainless steel to the tool surface was evaluated, the test equipment was set to a single, forward stroke mode. Dry sliding conditions with a sliding speed fixed to 0,01 m/s were used.

To determine the frictional behaviour of the investigated materials against austenitic stainless steel under starved lubricated conditions, the load-scanning test rig was set to multicycle mode. An approximately 10-µm-thick film of pure poly-alpha-olefin oil (PAO, v_{40} = 46,6 mm^2/s) was applied to the austenitic stainless steel sample before each test.

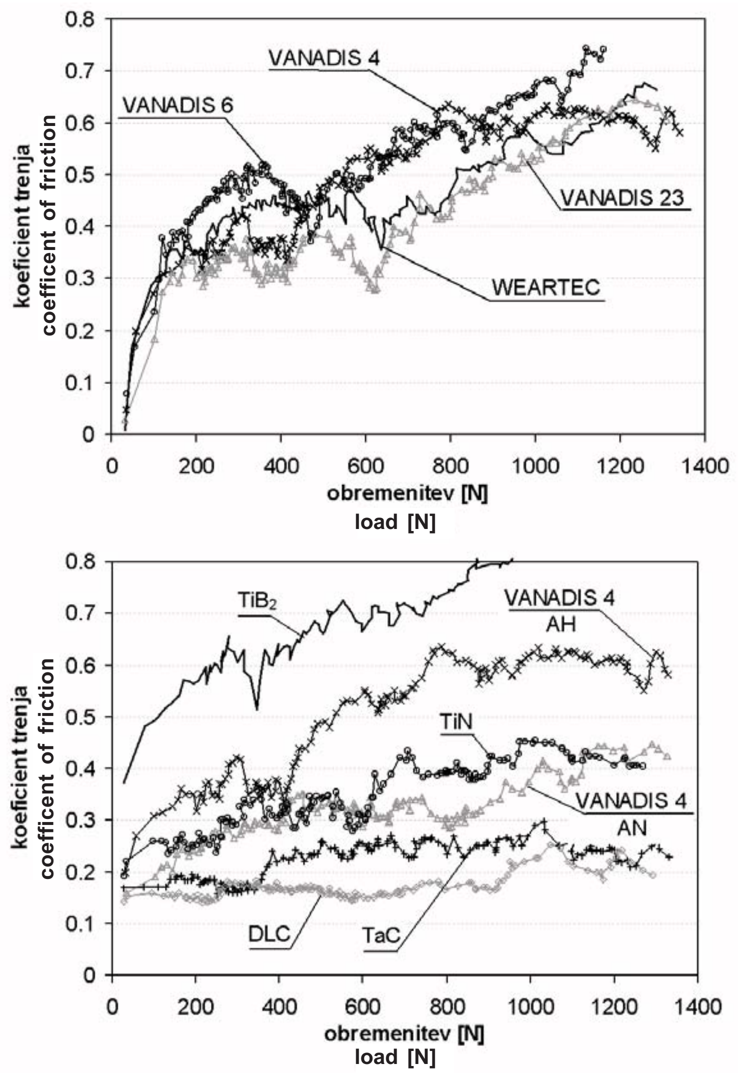
The same test procedure, with the sliding speed of 0.1 m/s, the multicycle mode and the use of lubricant was used to determine the wear resistance of different materials and coatings under boundary lubrication. However, a hardened ball-bearing steel had to be used as the counter material to induce wear of the investigated materials and coatings. The maximum number of test cycles was 200. During testing the coefficient of friction was monitored as a function of load and time, and after the completion of the test a critical load corresponding to the appearance of material transfer and wear of the investigated materials were determined by post-test optical microscopy (OM) and optical surface profilometry, respectively.

2 REZULTATI

Slika 2 prikazuje torne lastnosti raziskovanih materialov v obliki koeficienta trenja kot funkcijo obremenitve. V primeru kaljenega jekla vanadis 4 se začetni koeficient trenja giblje v območju med 0,3 in 0,35. Prvi znaki adhezije avstenitnega jekla na dotikalno površino orodnega jekla se, v obliki nenadnega povečanja koeficienta trenja, kažejo pri obremenitvi ~200 N, kar je mikroskopija dotikalne površine tudi potrdila. Podobno obnašanje je moč zaslediti pri vseh orodnih jeklih, vključenih v raziskavo, kar prikazuje slika 2a. V odvisnosti od obremenitve, pri kateri se prične na dotikalni površini orodnega jekla ustvarjati plast prenesenega avstenitnega jekla, pa je moč raziskovana orodna jekla razdeliti v dve skupini (sl. 3a). Pri prvi skupini, ki

2 RESULTS AND DISCUSSION

Figures 2a and b reveal the anti-sticking properties as the monitored friction coefficient versus load in the dry sliding test. In the case of hardened vanadis 4 steel against austenitic stainless steel the initial friction coefficient varied between 0.30 and 0.35. The first sign of adhesion of work material to the tool-steel surface, as indicated by a sudden increase in friction and confirmed by post-test microscopic observation, was detected at a load of about 200 N. Similar results with only marginal differences in frictional behaviour were observed for all the forming-tool steels investigated, as shown in Fig. 2a. However, depending on the load at which a layer of stainless steel starts to build-up on the tool surface, the investigated forming-tool steels can be classified into



Sl. 2. *Koeficient trenja v odvisnosti od obremenitve; (a) orodna jekla za hladno preoblikovanje in (b) oplemeniteno orodno jeklo za hladno preoblikovanje vanadis 4*

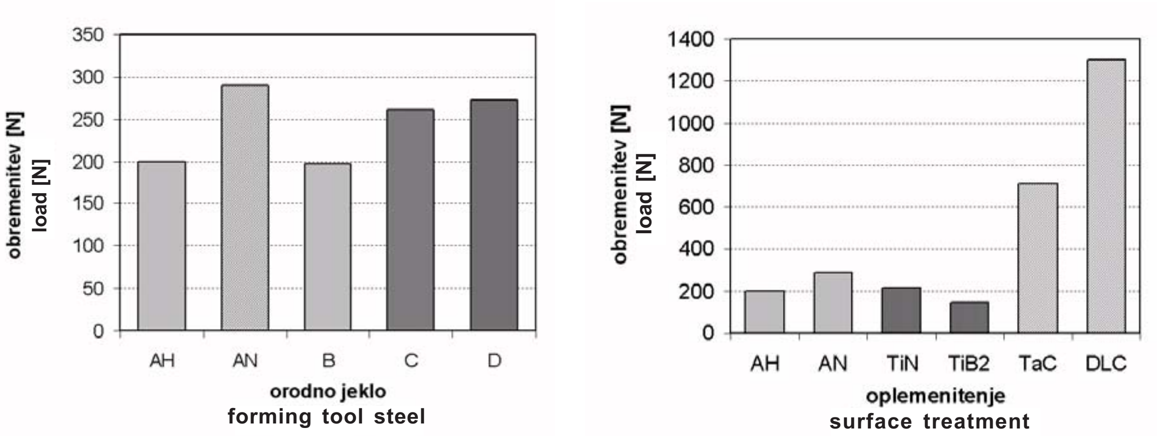
Fig. 2. *Friction coefficient vs. normal load for (a) forming-tool steels and (b) surface-engineered vanadis 4 steel, recorded during sliding against stainless steel*

vključuje kaljeni jekli vanadis 4 in vanadis 6, se adhezija ter prenos avstenitnega jekla na dotikalno površino orodja prične pri obremenitvi, nižji od 200N. Pri jeklih vanadis 23 in weartec, ki spadata v drugo skupino, pa v območju med 250 in 300N (sl. 3a).

Sliki 2b in 3b prikazujeta krivulje koeficienta trenja ter kritično obremenitev adhezije in prenosa avstenitnega jekla na dotikalno površino za primer oplemenitenega orodnega jekla vanadis 4. Tudi v primeru oplemenitenega orodnega jekla vanadis 4 nenadno povečanje koeficienta trenja sovpada s pričetkom adhezije oziroma lepljenjem avstenitnega jekla na dotikalno površino orodnega jekla. V primerjavi s kaljenim orodnim jeklom, nitriranje v plazmi, zniža koeficient trenja ter daje boljšo adhezijsko odpornost površine ($L_c \approx 300$N). Kljub vsemu pa z nitriranjem v plazmi ne moremo doseči izrednih tornih lastnosti, ki jih ponujata prevleki TaC in DPP, kar prikazujeta sliki 2b in 3b.

two groups, see Fig. 3a. For the first group with hardened vanadis 4 and vanadis 6 steel, the transfer of work material started at a load of approximately 200 N, whereas vanadis 23 and weartec steels displayed adhesion of the austenitic stainless steel in the load range 250 to 300 N, see Fig. 3a.

Figures 2b and 3b show coefficient-of-friction curves and critical loads of material transfer, respectively, for surface-engineered vanadis 4 steel. A sudden increase in the friction was found to correspond to the beginning of material transfer for the nitrided vanadis 4, and the vanadis 4 with TiN, TiB$_2$ and TaC coatings. Plasma nitriding improved the anti-sticking properties of vanadis 4 ($L_c \approx 300$ N), which then outperformed all the other forming-tool steels investigated. However, the plasma-nitrided surfaces were unable to match the very good behaviour obtained with the TaC and DLC coatings, as shown in Figs. 2b and 3b.



Sl. 3. *Kritična obremenitev pričetka prenosa in tvorjenja plasti avstenitnega jekla na dotikalni površini raziskovanih materialov, določena z optično mikroskopijo; (a) orodna jekla za hladno preoblikovanje (preglednica 3) in (b) oplemeniteno orodno jeklo za hladno preoblikovanje vanadis 4*

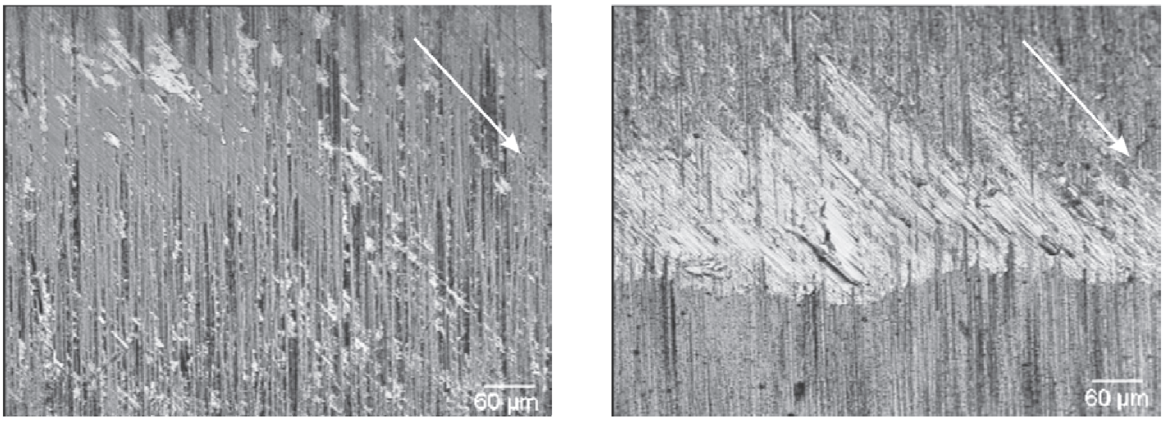
Fig. 3. *Beginning of the transfer of stainless steel to (a) forming-tool steels and (b) surface-engineered vanadis 4 steel*

Prevleki TaC in DPP znižata začetni koeficient trenja (μ ≈ 0,15, sl. 2b) ter dajeta najmanjšo verjetnost prenosa obdelovanega materiala. Pri prevleki TaC se je adhezija in prenos avstenitnega jekla pričela pri obremenitvi ~700 N, medtem ko pri prevleki DPP tudi pri največji obremenitvi 1300N ni prišlo do nastajanja povezane plasti prenesenega avstenitnega jekla na dotikalni površini, kakor prikazuje slika 4a. Na drugi strani pa prevleka TiB_2 kaže najvišji koeficient trenja proti avstenitnemu jeklu (μ = 0,5 - 0,8) in takojšen prenos obdelovanega materiala na dotikalno površino orodja (slika 4b). Kljub temu, da je uporaba prevleke TiN znižala začetni koeficient trenja na ~0,25 pa, v primerjavi s kaljenim orodnim jeklom, to ni imelo nikakršnega vpliva na postopek prenosa obdelovanega materiala, kakor prikazuje slika 3b.

Spremljanje koeficienta trenja v odvisnosti od obremenitve in števila ponovitev omogoča izdelavo tornih kart, ki prikazujejo spremembe v

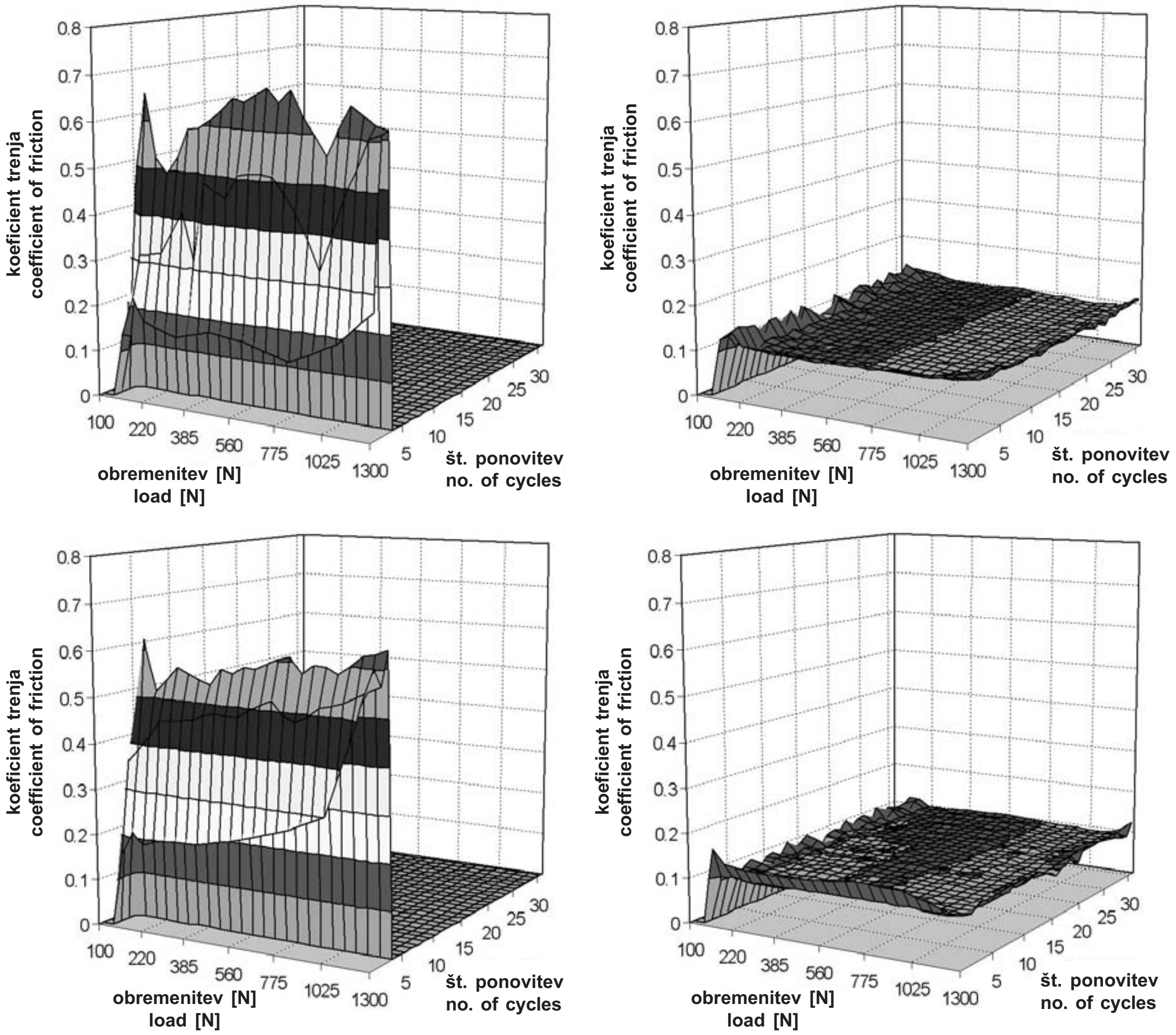
The TaC and DLC coatings considerably reduced the initial friction coefficient against austenitic stainless steel (μ ≈ 0.15, see Fig. 2b) and gave the lowest sensitivity to material transfer. For the TaC coating, the transfer of stainless steel started at a load of around 700 N, whereas virtually no transfer of work material could be detected for DLC-coated vanadis 4 steel up to a maximum load of 1300 N, as shown in Fig. 4a. On the other hand, the TiB_2 coated steel showed by far the highest friction coefficient (0.5–0.8), and an almost instantaneous transfer of stainless steel to the coated surface (Fig. 4b). The application of a TiN coating reduced the initial friction coefficient to about 0.25, but this did not have any influence on the process of material transfer in comparison to uncoated vanadis 4 steel, see Figs. 3a and b.

Monitoring the friction coefficient as a function of load and time makes it possible to prepare friction maps, which show the transition points in the



Sl. 4. *Izgled dotikalne površine pri pričetku prenosa avstenitnega jekla; (a) DPP prevleka pri obremenitvi 1300 N in (b) TiB_2 prevleka pri obremenitvi 150 N*

Fig. 4. *Typical appearance of the contact surfaces of sliding-test specimens at the begining of stainless-steel transfer (light contrast). a) DLC coating at 1300 N load, and (b) TiB_2 coating at 150 N load. The arrows indicate the direction of sliding*



Sl. 5. *Torne slike za oplemeniteno orodno jeklo vanadis 4: (a) nitrirano v plazmi + PAO, (b) nitrirano v plazmi + izbrano olje za hladno preoblikovanje, (c) prevlečeno s prevleko TiN + PAO in (d) prevlečeno z DPP prevleko + PAO*

Fig. 5. *Friction maps for surface-engineered vanadis 4 steel, sliding against soft austenitic stainless steel. (a) plasma-nitrided steel + PAO, (b) plasma-nitrided steel + fully formulated forming oil – Castrol Ilform, (c) TiN coated steel + PAO, (d) DLC coated steel + PAO*

tornem obnašanju oplemenitenega orodnega jekla vanadis 4 (sl. 5). V primeru kaljenega ali nitriranega orodnega jekla za delo v hladnem je prišlo do prehoda iz začetnega mejnega mazanja v področje suhega trenja med drugo ponovitvijo, in to pri obremenitvi ~400 N, po vsega treh ponovitvah pa je bilo treba preizkus zaradi čezmernega prenosa obdelovanega materiala ustaviti (sl. 5a). Podobno torno obnašanje z začetnim koeficientom trenja v območju med 0,15 in 0,2 ter prehod v področje suhega trenja že med drugo ponovitvijo, smo opazili pri vseh raziskovanih orodnih jeklih za delo v hladnem. Z uporabo izbranega olja za hladno preoblikovanje (Castrol Ilform TDN 81, v_{40} = 120 mm^2/s) smo že z nanosom ~10 μm mazalne plasti na dotikalno površino zagotovili enakomeren potek koeficienta trenja v celotnem obremenilnem območju in popolnoma

tribological behavior of the investigated materials. Friction maps for plasma-surface-treated vanadis 4 steel loaded against austenitic stainless steel under starved lubrication conditions are shown in Fig. 5. An increase in the friction was detected as early as the second stroke, at ≈ 400 N load, for the hardened or plasma-nitrided steel, and the test had to be stopped due to the extensive transfer of stainless steel to the tool-steel surface after the third stroke, as indicated in Fig. 5a. These results indicate that as the reciprocal sliding proceeds, the initial regime of boundary lubrication moves towards a mixture of boundary lubrication and dry sliding. Similar results, with the initial friction in the range 0.15 to 0.20, and the transfer of work material starting during the second stroke, were observed for all forming-tool steels investigated. However, the use of a fully formulated forming oil gave a very smooth sliding of the nitrided preprečili prenos obdelovanega materiala, kar prikazuje slika 5b.

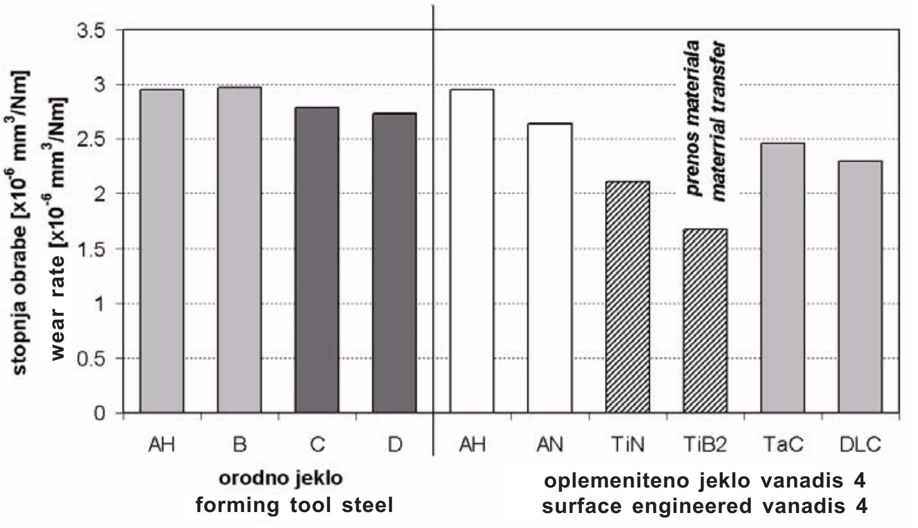
Pri uporabi trdih keramičnih prevlek TiN in TiB_2 je prišlo do preboja mazalne plasti in prehoda v področje suhega trenja s prenosom obdelovanega materiala že med prvo ponovitvijo, zaradi česar je bilo treba preizkus ustaviti že po dveh ponovitvah (sl. 5c). Na drugi strani pa prevleki na podlagi trdega ogljika (TaC in DPP) zagotavljata precej boljše torne lastnosti dotikalne površine. Kljub temu, da je tudi v primeru prevleke TaC prišlo do preboja mazalne plasti in prenosa obdelovanega materiala, je bilo to omejeno le na največje obremenitve ($F_N \geq 1000$ N). Ti rezultati kažejo na slabo nosilnost same prevleke oziroma pomanjkljivo oprijemljivost prevleke na podlago. Najboljše rezultate, primerljive z uporabo izbranega olja za hladno preoblikovanje in neoplaščenega jekla vanadis 4, pa smo dosegli z uporabo prevleke DPP, ki daje že ob najmanjši količini neaditiviranega PAO olja enakomeren koeficient trenja ($\mu \sim 0{,}1$) in popolno zaščito pred prenosom obdelovanega materiala v celotnem obremenitvenem območju (sl. 5d).

Razlika v obrabni obstojnosti raziskovanih materialov, določeni v pogojih mejnega mazanja, je bila precej manjša kakor v primeru tornih lastnosti. Slika 6 prikazuje stopnjo obrabe raziskovanih materialov v točki vzdolž dotikalne poti, ki ustraza obremenitvi 700 N oziroma dotikalnemu tlaku ≈ 4,2 GPa. Na splošno je moč reči, da nitriranje v plazmi ter nanos trde prevleke izboljšata obrabno obstojnost orodnega jekla, kar velja za celotno obremenitveno območje (sl. 6). Kljub vsemu pa razlaga rezultatov obrabnih preizkusov ni preprosta, saj hkrati deluje več obrabnih mehanizmov.

steel ($\mu \approx 0.1$) and complete protection against material transfer, see Fig. 5b.

Figures 5c and d show friction maps for the coated forming-tool steel loaded against austenitic stainless steel. In the case of TiN-coated steel, a rapid increase in friction corresponding to a rapid transfer from boundary lubricated to dry sliding started as early as the first stroke, at a load of approximately 1100 N (Fig. 5c). The TiB_2 coating showed similar results with an even higher increase rate in friction under starved lubricated conditions (0.4–0.6), and an immediate transfer of stainless steel. On the other hand, TaC- and DLC-coated samples showed improved frictional properties under starved lubrication conditions, in comparison with uncoated steel. For the TaC coating, an increase in friction was also detected during the second stroke; however, it was more load dependent with the adhesion of the work material limited to the highest loads ($F_N \geq 1000$ N). Due to insufficient adhesion, the TaC coating may fail under high loads, leading to exposure of the substrate material, and accelerated material transfer. By far the best results were obtained for the DLC-coated steel, which during the entire 50-cycle test displayed a uniform frictional behavior with a friction coefficient of ~0.1, see Fig. 5d.

The differences in wear resistance among the test materials were not as dramatic in terms of sliding wear under boundary lubrication as they were in terms of friction, see Fig. 6. It shows the wear rate of the investigated materials measured using a profilometric technique at a position corresponding to a load of 700 N (≈ 4.2 GPa maximum Hertzian contact pressure). Similar results were observed for the whole load range. The general observations are that plasma nitriding or coating deposition improve the wear resistance of the surfaces. However, it is not at all straightforward to interpret the sliding-wear test results, since several mechanisms are operating simultaneously.



Sl. 6. *Stopnja obrabe raziskovanih materialov (mejno mazanje, PAO, F_N = 700 N, 200 ponovitev)*
Fig. 6. *Wear rate of investigated materials loaded against ball-bearing steel under starved lubrication conditions (POA, F_N = 700 N, 200 cycles)*

Na splošno bi morala dati kombinacija velike trdote prevleke in nizkega koeficienta trenja tudi majhno stopnjo obrabe. V našem primeru protimaterial (jeklo za kroglične ležaje, 100Cr6) vsebuje majhen delež trdih delcev (Cr in Fe karbidi), ki lahko povzročijo abrazijsko obrabo raziskovanih materialov. S tega vidika naj bi dala uporaba trdih prevlek precejšnje izboljšanje obrabne obstojnosti dotikalne površine. Po drugi strani pa se lahko delci prevleke vtisnejo v »mehak« protimaterial in povzročijo razenje same prevleke. Kar se tiče trenja pa visok koeficient trenja pospešuje adhezijo in prenos protimateriala na oplaščeno površino, ki nato preprečuje nadaljnjo obrabo osnovne površine.

Kakor v primeru tornih lastnosti (sl. 2a) je tudi razlika v obrabni obstojnosti raziskovanih orodnih jekel za hladno preoblikovanje najmanjša. Ponovno pa jekli vanadis 23 in weartec kažeta nekoliko boljšo obrabno obstojnost, kar prikazuje slika 6. Na drugi strani daje uporaba postopka nitriranja v plazmi tudi do 20% boljšo obrabno obstojnost orodnega jekla vanadis 4. V primeru oplaščenega orodnega jekla sta prevleki TiN in TiB_2 precej presegli obrabno obstojnost prevlek z izjemnimi tornimi lastnostmi, prevlek TaC in DPP (sl. 2b). Dobljene rezultate je moč razložiti s tvorjenjem plasti prenesenega protimateriala na površini keramične prevleke, ki nato ščiti prevleko pred obrabo. V primeru prevleke TiB_2 je bilo treba obrabni preizkus zaradi čezmernega prenosa materiala celo ustaviti, in to že po vsega 15 ponovitvah.

V primeru orodij za hladno preoblikovanje je zmožnost površine preprečevati adhezijo in prenos obdelovanega materiala pogosto precej bolj pomembna kakor njena obrabna obstojnost. Tako obrabno obstojni prevleki TiN in TiB_2, z visokim koeficientom trenja in veliko verjetnostjo adhezije ter prenosa obdelovanega materiala na dotikalno površino orodja, ne pomenita najboljše rešitve za izboljšanje lastnosti orodij za hladno preoblikovanje. Poleg tega lahko slaba kakovost prevleke privede do njenega luščenja in posledično do poškodbe izredno dragega preoblikovalnega orodja. Ker daje sprememba v sestavi in/ali mikrostrukturi jekla za hladno preoblikovanje omejene možnosti izboljšanja tornih in obrabnih lastnosti površine, je nitriranje v plazmi trenutno najprimernejši način izboljšanja triboloških lastnosti in obstojnosti preoblikovalnih orodij. Na drugi strani prevleka DPP, z dobro obrabno obstojnostjo in izjemnimi tornimi lastnostmi ter zmožnostjo preprečevati adhezijo obdelovanega materiala na dotikalno površino orodja, kaže izjemen potencial v preoblikovalni industriji.

3 SKLEPI

- Vsa orodna jekla za delo v hladnem, vključena v raziskavo, imajo podobne torne in protiobrabne lastnosti, pri čemer jekli vanadis 23 in weartec rahlo izstopata.
- V primerjavi s kaljenjem daje nitriranje v plazmi tudi

Generally, high hardness in combination with low friction should give a low wear rate. The counter material (ball-bearing steel) contains a small volume content of hard particles in the form of μm-sized Cr and Fe carbides (about 1200–1500 HV), which could wear some of the tested surfaces abrasively. Thus, a hard coating would act beneficially. On the other hand, wear fragments from the coatings and treated tool-steel surfaces could possibly be embedded in the counter material and act as abrasives against the test materials. As to the friction, a high friction promotes adhesion of the counter material to the wearing surface, which may prevent further wear.

As in the case of the friction against stainless steel (Fig 2a), all forming-tool steels were rather difficult to separate when comparing wear in the sliding test against ball-bearing steel, see Fig. 6. Vanadis 23 and weartec did display a slightly better wear resistance than the other samples. On the other hand, plasma nitriding gave up to 20% higher wear resistance of vanadis 4 steel. In the case of coated tool steel, the TaC and DLC coatings, giving the lowest friction (Fig. 2b) were outperformed by the TiN and TiB_2 coatings. This is likely to be explained by the protective action of the adhered work material, which appeared most frequently on the latter coatings. With the TiB_2 coating, the wear tests had to be stopped after approximately 15 cycles due to extensive material transfer and building up of a thick layer of counter material on the coated surface.

In the case of forming tools, the ability of the surface to prevent the adhesion of work material is often more important than its wear resistance. Therefore, hard wear-resistant ceramic coatings of TiN and TiB_2 with a high tendency for material transfer do not represent the best solution. In addition, poor adhesion of the coating may lead to coating spallation, causing a deterioration in the forming tool's performance instead of the expected improvement. Since changes in forming-tool steel's composition and/or structure gives limited improvement in tool performance, plasma nitriding represents the most reliable way of improving the tribological properties of forming tools. On the other hand, the DLC coating was found to prevent any transfer of work material to the coated surface even under starved lubrication by non-additivated PAO, Fig. 6. Assuming that adequate coating-to-substrate adhesion is obtained, DLC coatings seem to be the best solution for improving the tribological properties of forming tools.

3 CONCLUSIONS

- All the forming-tool steels investigated give comparable friction and wear results when tested in a load-scanning test rig against soft austenitic stainless steel and ball-bearing steel, respectively. However, vanadis 23 and weartec show a slight do 50% boljšo adhezijsko odpornost proti avstenitnemu jeklu ter do 20% boljšo obrabno obstojnost orodnega jekla za hladno preoblikovanje.

- Kljub temu, da dajeta prevleki TiN in TiB_2 najboljšo obrabno obstojnost, pa velika verjetnost prenosa obdelovanega materiala na dotikalno površino orodja omejuje njuno praktično uporabo. Izjemen potencial pri preoblikovanju avstenitnega jekla pomeni mehkejša prevleka na podlagi trdega ogljika (DPP) z dobro obrabno obstojnostjo ter odličnimi tornimi lastnostmi.
- Ob doseganju ustrezne oprijemljivosti prevleke na podlago bi lahko uporaba prevlek na podlagi trdega ogljika omejila ali celo izločila uporabo maziv v postopku hladnega preoblikovanja.

Zahvala

Delo je nastalo s finančno pomočjo Uddeholm Toolong AB, Švedskega raziskovalnega sveta in Carl Trygger ustanove. Zahvala gre tudi Uddeholm Tooling in Balzers Sandvik Coating AB za pripravo preizkušancev in nanos DPP prevlek, Urbanu Wiklundu in Danielu Nilssonu z Univerze v Uppsali za pripravo prevlek TiN, TaC in TiB_2, ter Vojtehu Leskovšku z Inštituta za kovinske materiale in tehnologije v Ljubljani za izvedbo nitriranja v plazmi.

advantage over the rest.

- After plasma nitriding, the vanadis 4 steel outperformed all the other forming-tool steels investigated in terms of anti-sticking properties as well as wear resistance. Therefore, plasma nitriding represents a reliable way of improving the tribological performance of forming-tool materials.
- Although the hard TiN and TiB_2 coatings showed the best wear resistance, they possess a high tendency to pick up work material. On the other hand, the softer DLC coating with its excellent anti-sticking properties and sufficiently good wear resistance shows a high potential for use in forming-tool applications.
- On the condition that adequate coating-to-substrate adhesion is obtained, the use of DLC-coated forming tools could limit or even eliminate the use of lubricants in cold-forming applications.

Acknowledgements

Uddeholm Toolong AB, The Swedish Research Council and Carl Trygger Foundation are greatly acknowledged for their financial support. The supply of test materials and DLC coatings from Uddeholm Tooling and Balzers Sandvik Coating AB, respectively, is much appreciated. Many thanks go also to Urban Wiklund and Daniel Nilsson for preparation of the TiN, TaC and TiB_2 coatings and to Vojteh Leskovšek for preparation of the plasma-nitrided samples.

4 LITERATURA
4 REFERENCES

[1] Bhushan, B. (2000) Modern tribology handbook. CRC Press, NY.

[2] Imbeni, V., C. Martini, E. Lanzoni, G. Poli, I.M. Hutchings (2001) Tribological behaviour of multi-layered PVD nitride coatings. *Wear* 251, 997–1002.

[3] Hogmark, S., S. Jacobson, M. Larsson, U. Wiklund (2000) Mechanical and tribological requirements and evaluation of coating composites, in modern tribology handbook. ed. B. Bhushan. *CRC Press*, NY.

[4] Renevier, N.M., J. Hamphire, V.C. Fox, J. Witts, T. Allen, D.G. Teer (2001) Advantages of using self-lubricating, hard, wear-resistant MoS_2 -based coatings. *Surface and Coatings Technology* 142-144, 67-77.

[5] Holmberg, K., A. Matthews. (1994) Coatings tribology. *Elsevier Tribology Series 28*. Elsevier, Amsterdam.

[6] Erdemir, A., F.A. Nichols, X.Z. Pan, R. Wei, P. Wilbur (1993) Friction and wear performance of ion-beam-deposited diamond-like carbon films on steel substrates. *Diamond and Related Materials 3*, 119-125.

[7] Kodali, P., K.C. Walter, M. (1997) Nastasi, Investigation of mechanical and tribological properties of amorphous diamond-like carbon coatings. *Tribology International* 30, 591-598.

[8] Wanstrand, O., N. Axen, R. Fella (1997) A tribological study of PVD coatings with carbon-rich outer layers. *Surface and Coatings Technology* 94-95, 469-475.

[9] Rincon, C., G. Zambrano, A. Carvajal, P. Prieto, H. Galindo, E. Martinez, A. Lousa, J. Esteve (2001) Tungsten carbide/diamond-like carbon multilayer coatings on steel for tribological applications. *Surface and Coatings Technology* 148, 277-283.

[10] Hogmark, S., S. Jacobson, O. Wanstrand (1999) A new universal test for tribological evaluation. *Proceedings of the 21^{st} IRG-OECD Meeting*, Amsterdam.

[11] Hogmark, S., S. Jacobson, O. Wanstrand (2000) The Uppsala loadscanner – an Update. *Proceedings of the 22^{st} IRG-OECD Meeting*, Cambridge.

Naslovi avtorjev: doc.dr. Bojan Podgornik
Univerza v Ljubljani
Fakulteta za strojništvo
Center za tribologijo in tehnično diagnostiko
Bogišičeva 8
1000 Ljubljana
bojan.podgornik@ctd.uni-lj.si

prof. Sture Hogmark
The tribomaterials group
Ångström Laboratory
Univerza v Uppsali
Box 534
SE- 751 21 Uppsala

dr. Odd Sandberg
Uddeholm Tooling AB
SE-683 85 Hagfors

Authors' Addresses: Doc.Dr. Bojan Podgornik
University of Ljubljana
Faculty of Mechanical Eng.
Centre for Tribology and Technical Diagnostics
Bogišičeva 8
SI- 1000 Ljubljana
bojan.podgornik@ctd.uni-lj.si

Prof. Sture Hogmark
The tribomaterials group
Ångström Laboratory
Uppsala University
Box 534
SE- 751 21 Uppsala

Dr. Odd Sandberg
Uddeholm Tooling AB
SE-683 85 Hagfors

Prejeto:
Received: 17.12.2002

Sprejeto:
Accepted: 8.4.2004

Odprto za diskusijo: 1 leto
Open for discussion: 1 year