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Obrabna odpornost konstrukcijskega jekla, nitriranega v plazmi

Wear Resistance of Plasma Nitrided Structural Steel

Bojan Podgornik - Jože Vižintin - Vojteh Leskovšek

V raziskavi je bila določena obrabna odpornost konstrukcijskega jekla 42CrMo4, nitriranega v plazmi in pulzirajoči plazmi, pri čemer je bilo kaljenje uporabljeno kot primerjava. Raziskana je bila tako drsna obrabna odpornost kakor tudi odpornost proti jamičenju, in to za pogoje mazanega dotika. Vpliv nitriranja je bil določen z uporabo metalografije, merjenjem mikrotrdote in zaostalih napetosti ter raziskavo topografije površine. Drsna obrabna odpornost je bila določena na napravi "valjček-plošča", medtem ko je bila odpornost proti jamičenju določena na napravi za preskušanje zobnikov.

Rezultati raziskave so pokazali, da se obrabna odpornost konstrukcijskega jekla, še posebej odpornost proti jamičenju, po nitriranju v plazmi občutno izboljša. Primerjava obrabne odpornosti raziskovanega jekla, nitriranega v plazmi in nitriranega v pulzirajoči plazmi, pa je pokazala zelo enakovredno obrabno odpornost.

(Ključne besede: nitriranje plazemsko, nitriranje plazemsko pulzno, jamičenje, drsenje, obraba)

In our study wear resistance of plasma and pulse plasma nitrided 42CrMo4 steel was evaluated under lubricated sliding and pitting wear conditions, where hardened samples were used as a reference. The nitrided samples were characterised using metallograpy, microhardness, residual stress and surface examination techniques. After surface treatment, lubricated sliding wear tests were performed on a pin-on-disc machine in which surface treated pins were loaded against hardened ball bearing steel discs. Pitting wear tests were performed on back-to-back gear test rig.

Experimental results indicate, that the wear resistance of 42CrMo4 steel, especially pitting wear resistance can be greatly improved by means of plasma and pulse plasma nitriding. However, plasma and pulse plasma nitrided 42CrMo4 steel showed very similar sliding and pitting wear resistance.

(Keywords: plasma nitriding, pulse plasma nitriding, pitting, sliding, wear)

0 UVOD

Za izboljšanje obstojnosti zobnikov se uporabljajo različni kemotermični postopki poboljšanja, to so ogličenje, plamensko ali indukcijsko kaljenje ter plinsko nitriranje. Kljub temu, da je ogljičenje eden od najpogostejših in tudi najbolj učinkovitih postopkov izboljšanja, ima svoje omejitve pri izboljšanju zobnikov velikih izmer [1]. Na drugi strani kaljenje z visokih temperatur avstenitizacije pogosto privede do nepričakovanih in nezaželenih deformacij zobnikov [2], pri postopku običajnega plinskega nitriranja pa pride do nastajanja večfazne spojinske plasti na površini [3]. Spojinska ali bela plast, nastala med postopkom nitriranja, je krhka in drobljiva, kar lahko privede zaradi zaostalih napetosti do njenega krušenja med samim delovanjem

0 INTRODUCTION

Gear manufacturers have employed techniques such as carburizing, flame hardening, induction hardening, and gas nitriding to increase the strength of gearing components. Although carburizing is one of the most common and effective surface-hardening methods used to improve the load-carrying capacity of gears, its use in the production of large gears has been very problematic [1]. Another method, known as quench hardening, which involves quenching from a high austenitizing temperature, often results in unpredictable levels of tooth deflection, helix angle change, and overall distortion [2]. During conventional gas-and-bath nitriding, a multiphase compound layer is formed on the surface [3]. This compound layer contains high residual stresses, which makes the layer friable and brittle. Such zobnikov. Zaradi tega je spojinska plast nezaželena in jo je treba pred uporabo elementov odstraniti z delovne površine [4].

Eden od novejših kemotermičnih postopkov, ki se uporablja za izboljšanje lastnosti zobnikov, je nitriranje v plazmi ([5] in [6]). Nitriranje v plazmi je ekološko čist proces, ki omogoča natančno in popolnoma avtomatizirano vodenje postopka difuzije dušika, kar pomeni nitriranje površin brez nastanka “škodljive” spojinske plasti [7]. Poleg tega, zaradi uporabe nižjih temperatur, nitriranje v plazmi ne povzroča deformacij elementov po izboljšanju [8], s čimer odpadejo zahteve po dodatni mehanski obdelavi delovne površine. Tehnološko novejši postopek nitriranja, nitriranje v pulzirajoči plazmi omogoča uporabo plazme zelo majhnih moči, kar zagotavlja bolj enakomerno porazdelitev temperatur, hkrati pa preprečuje pregrevanje površine. Z uporabo nitriranja v pulzirajoči plazmi je prav tako mogoče izboljšati različne vrste jekel [9].

Namen predstavljene raziskave je bil določiti obrabno odpornost jekla 42CrMo4, nitriranega v plazmi ter pulzirajoči plazmi pri drsenju in kotaljenju. Za primer uporabe nitriranja pri zobnikih je bilo treba narediti tribološko in ekonomsko oceno ustreznosti zamenjave postopka indukcijskega kaljenja s postopkom nitriranja v plazmi.

1 PRESKUSI

1.1 Priprava preskušancev

Preskušance smo izdelali iz jekla za izboljšanje in nitriranje 42CrMo4 (0,5%C, 1,0%Cr, 0,2%Mo), ki je bilo izboljšano na trdoto 300 $HV_{0.5}$. Pred kemotermično obdelavo so bili vsi preskušanci brušeni ($R_a \approx 0{,}35$ µm) ter razmaščeni.

Kemotermična obdelava preskušancev je obsegala nitriranje v plazmi, nitriranje v pulzirajoči plazmi ter postopek kaljenja (temperatura popuščanja 250 °C), ki smo ga uporabili kot primerjavo. Pogoji nitriranja so prikazani v preglednici 1 [10]. V vseh primerih je bila globina nitriranja 0,3 mm. Sami parametri nitriranja so bili izbrani tako, da je bil preprečen nastanek spojinske plasti na površini preskušanca.

1.2 Protiobrabni preskusi

Drsno obrabno odpornost kemotermično izboljšanega jekla 42CrMo4 smo določili na napravi “valjček-plošča”. Pri tem sta kemotermično obdelana valjčka pritiskala ob rotirajočo ploščo (sl. 1), narejeno iz orodnega jekla 90MnCrV8, izboljšano na trdoto 700 $HV_{0.5}$ in brušeno na $R_a \approx 0{,}4$ µm. Drsne protiobrabne preskuse smo izvedli pri sobni temperaturi (20 °C) in relativni vlažnosti zraka ~ 50%, drsni hitrosti 0,1 in 1 m/s ter obremenitvi 60 in 100 N. Za mazivo smo uporabili neaditivirano reduktorsko olje ISI VG68.

a layer is clearly undesirable and hence it has to be removed from the contact surfaces before the gears can be used [4].

Plasma nitriding is one of a new generation of heat-treatment processes that are being employed to improve the performance characteristics of gears ([5] and [6]). Plasma nitriding permits a fully automated and controlled nitrogen-diffusion process, which makes it possible to perform nitriding without any compound-layer formation [7]. The low temperatures used in plasma nitriding and the absence of any need to quench also ensure the minimum amount of distortion and dimensional variations [8]. Consequently, any subsequent grinding operations can be reduced or even eliminated by using a plasma-nitriding process. More advanced pulsed-plasma technology allows the use of the minimum plasma power for the process, which prevents overheating and ensures a uniform temperature distribution. Furthermore, almost every type of steel can be nitrided using pulsed-plasma technology [9].

The aim of the present investigation was to determine the sliding- and pitting-wear resistance of plasma-nitrided and pulsed-plasma-nitrided 42CrMo4 steel, and to perform a tribological and economic evaluation of the change from induction-hardened to plasma-nitrided gears.

1 EXPERIMENTAL

1.1 Sample preparation

The material used in this investigation was commercial 42CrMo4 structural steel for hardening and nitriding (0,5%C, 1,0%Cr, 0,2%Mo). Tempered specimens (300 $HV_{0.5}$) were ground ($R_a \approx 0{,}35$ µm) and degreased before plasma nitriding.

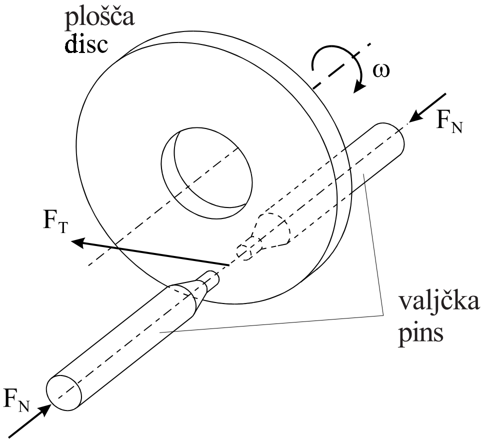
Plasma nitriding in both conventional and pulsed-plasma modes was carried out with a precise control of all the process parameters to form a nitrided case with a depth of 0.3 mm and a surface structure without any compound layer [10] (Table 1). One group of specimens was also hardened (oil quenched and tempered at 250°C) and used as a reference.

1.2 Wear tests

The sliding-wear resistance of the surface-treated 42CrMo4 steel was determined using a pin-on-disc machine. The pins were loaded against a rotating 90MnCrV8 steel disc (Fig. 1), hardened to 700 $HV_{0.5}$ and ground to an average roughness value of ~0.4 µm. Lubricated sliding-wear tests (additive-free ISI VG68 oil) were carried out at room temperature (~20°C) and a relative humidity of about 50%, with sliding speeds of 0.1 and 1 m/s and normal loads of 60 and 100 N.

Preglednica 1. *Postopki kemotermičnega izboljšanja in njihovi parametri*
Table 1. *Details of the surface treatment processes*

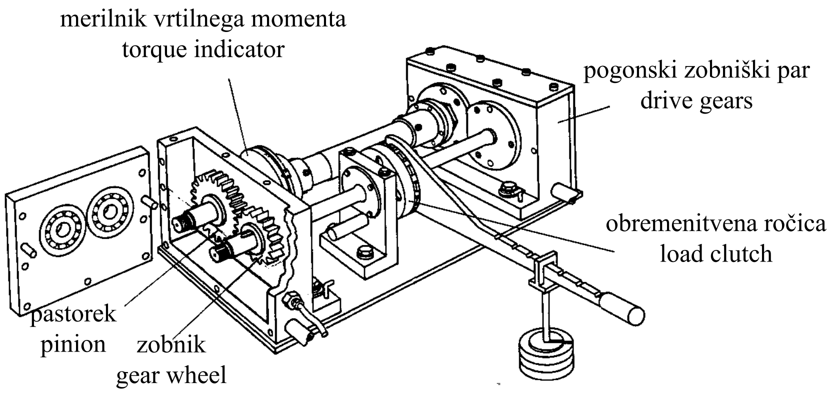
Postopek Process		Plinska mešanica Gas mixture	Temp. °C	Čas Time h	Tlak Pressure kPa	Utrip Pulse s
kaljenje hardening	A	kalilno olje quenched oil	870/250	2/1	-	-
nitriranje v plazmi plasma nitriding	B	99,4%H_2, 0,6%N_2	540	17	0,254	-
nitriranje v utrip. plazmi pulse plasma nitriding	C	99,4%H_2, 0,6%N_2	540	17	0,254	0,48/0,02



Sl. 1. *Shematičen prikaz naprave "valjček-plošča"*
Fig. 1. *Pin-on-Disc test rig*

Odpornost proti jamičenju smo določili na napravi za preskušanje zobnikov NPZ inštituta FZG (Forschungsstelle für Zahnräder und Getriebe), prikazani na sliki 2 [11]. Za preskus smo uporabili reduktorsko olje ISI VG68 ter standardne zobnike tipa C. Pri posameznem preskusu sta bila oba zobnika v paru izboljšana po enakem kemotermičnem postopku (pregl. 1). Preskus za jamičenje je potekal v dveh fazah. Po dveurnem vtekanju v peti stopnji (navor 94,1 Nm) je sledilo preskušanje v osmi stopnji (navor 239,3 Nm), in to dokler se ni pojavila poškodba jamičenja. Poškodba jamičenja je definirana kot poškodba več kot 4 odstotkov površine enega zobnega boka pastorka.

Pitting-wear tests were performed on back-to-back gear test rig BGTR (Fig. 2), designed by FZG institute (Forschungsstelle für Zahnräder und Getriebe) , and using C-type gears [11]. The same surface-treatment process was used for the pinion and the gear wheel (Table 1). The surface-treated gears were lubricated with ISI VG 68 formulated gear oil. The pitting-wear tests were carried out in a two-step process. After a running-in sequence (2 h at 94.1 Nm - stage 5) the test was run at 239.3 Nm torque (stage 8) until pitting failure occurred. The failure criterion was the occurrence of more than 4% of pitted area on one pinion tooth.



Sl. 2. *Shematičen prikaz NPZ*
Fig. 2. *BGTR gear test rig*

2 REZULTATI

2.1 Lastnosti površine

Z nitriranjem sta se povečali tako hrapavost površine kakor tudi mikrotrdota raziskovanega jekla [12]. Spremembo hrapavosti površine smo izmerili z dotikalnim merilnikom hrapavosti. Srednje odstopanje profila površine se je po nitriranju z začetnih 0,35 μm povečalo na ~ 0,65 μm. Za oba načina nitriranja, nitriranje v plazmi in nitriranje v pulzirajoči plazmi, smo izmerili podobne vrednosti srednjega odstopanja profila (sl. 3).

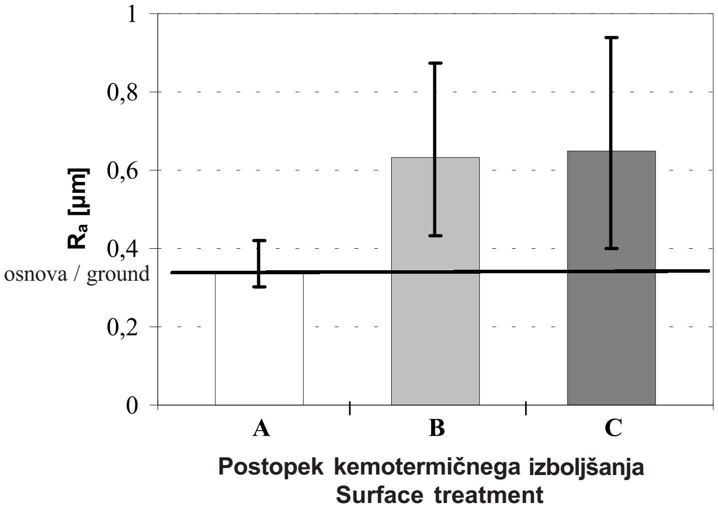
Rezultati meritev mikrotrdote površine kemotermično izboljšanega jekla 42CrMo4 so prikazani na sliki 4. V primerjavi s kaljenim jeklom s trdoto površine ~ 600 $HV_{0.5}$, se mikrotrdota površine po nitriranju v plazmi ali pulzirajoči plazmi poveča na ~ 700 $HV_{0.5}$ (sl. 4). Zaostale napetosti kemotermično izboljšanega jekla

2 RESULTS

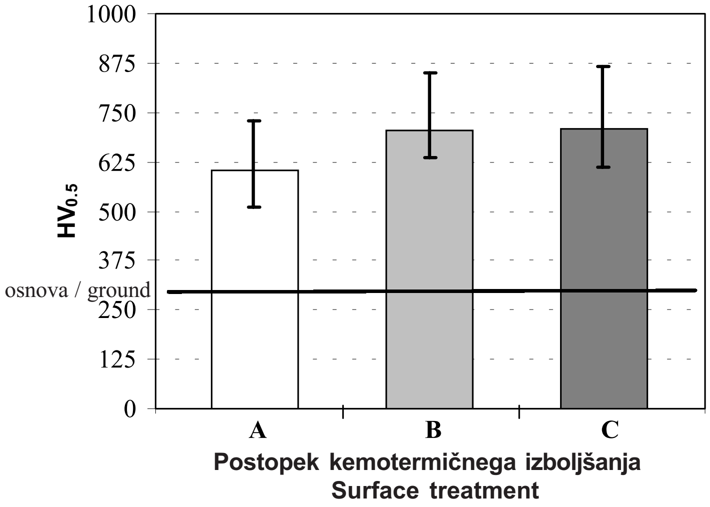
2.1 Surface properties

After nitriding, both the average roughness value and the maximum peak-to-valley height increased in comparison with the original ground surface [12]. The average roughness of the original surface changed from 0,35 μm to approximately 0,65 μm, measured for conventional and pulsed-plasma-nitrided specimens (Fig. 3).

The characteristic surface microhardness of surface-treated 42CrMo4 steel is shown in Fig. 4. Compared to hardening with the highest obtainable surface hardness of ~600 $HV_{0.5}$ and a constant hardness throughout the entire range from the surface to the centre of the specimen, plasma nitriding increased the surface hardness of the investigated steel to approximately 700 $HV_{0.5}$. For all the surface-treatment



Sl. 3. *Hrapavost površine kemotermično izboljšanega jekla 42CrMo4 (razpredelnica 1)*
Fig. 3. *Surface roughness of treated 42CrMo4 steel (Teble 1)*



Sl. 4. *Trdota površine kemotermično izboljšanega jekla 42CrMo4 (razpredelnica 1)*
Fig. 4. *Surface microhardness of treated 42CrMo4 steel (Table 1)*

42CrMo4 smo izmerili z metodo vrtanja luknjice [13]. Rezultati meritev zaostalih napetosti so pokazali, da vsi raziskovani postopki kemotermičnega izboljšanja površine povzročijo nastanek tlačnih zaostalih napetosti v materialu. S kaljenjem jekla smo dosegli enakomerno porazdelitev zaostalih napetosti z globino, z največjo vrednostjo ~ 50 MPa. Po nitriranju v plazmi oz. pulzirajoči plazmi pa smo dosegli precej večje vrednosti zaostalih napetosti, katerih največja vrednost (~ 220 MPa) je bila izmerjena 120 do 150 µm pod površino, kar prikazuje slika 5.

2.2 Protiobrabna odpornost

2.2.1 Drsni preskus

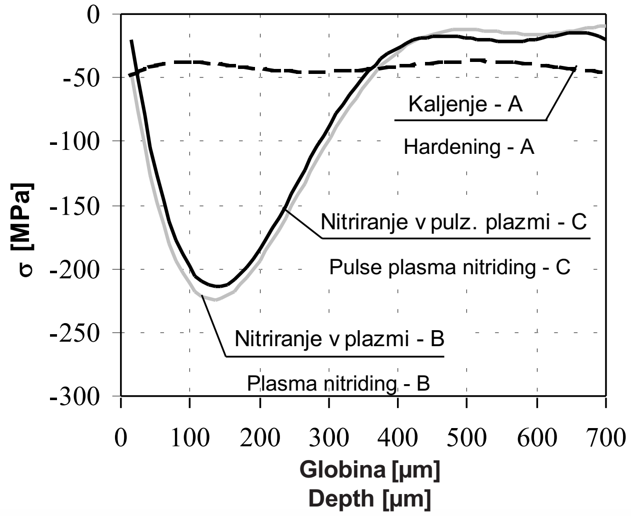
Rezultati preskušanja na napravi "valjček-plošča" kažejo, da je koeficient trenja raziskovanega jekla praktično neodvisen od uporabljenega postopka kemotermičnega izboljšanja (sl. 6). Pri obremenitvi 60 N je bila povprečna vrednost koeficienta trenja ~ 0,1. S povečanjem obremenitve

processes used the residual stresses, measured by the hole-drilling method [13], were found to be compressive. In the case of hardening, a uniform stress field was observed with a maximum residual stress of approximately 50 MPa. Nitriding gives much higher residual stresses with a maximum of ~220 MPa observed approximately 120 µm below the surface (Fig. 5). As in the case of surface roughness and surface microhardness, very similar residual stress distributions were caused by conventional and pulsed-plasma nitriding, as shown in Fig. 5.

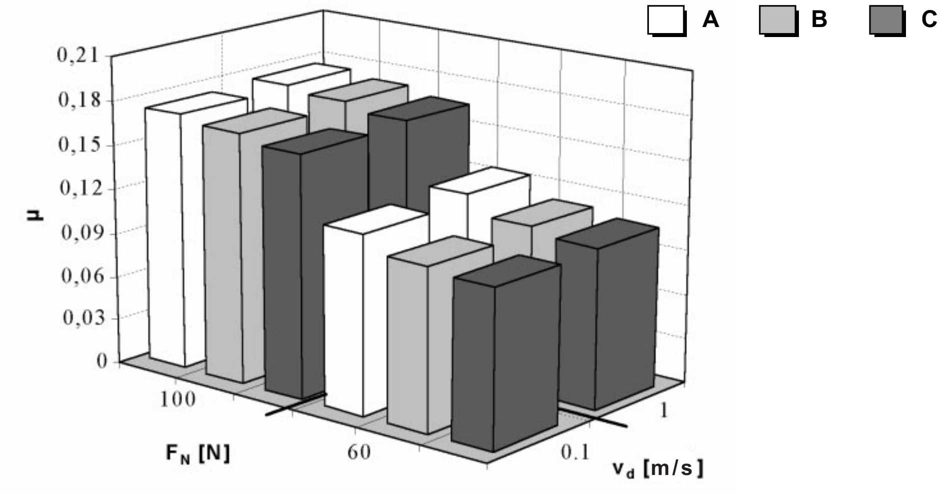
2.2 Wear properties

2.2.1 Sliding-wear test

From the pin-on-disc tests it was found that under all the test conditions the coefficient of friction was largely independent of the differences among the surface treatments used in this study, as shown in Fig. 6. For the case of the low load (60N) the steady-state coefficient of friction, measured at the end of the test, was



Sl. 5. *Porazdelitev zaostalih napetosti za različne postopke kemotermične obdelave (preglednica 1)*
Fig. 5. *Residual stress distribution as a function of surface treatment (Table 1)*



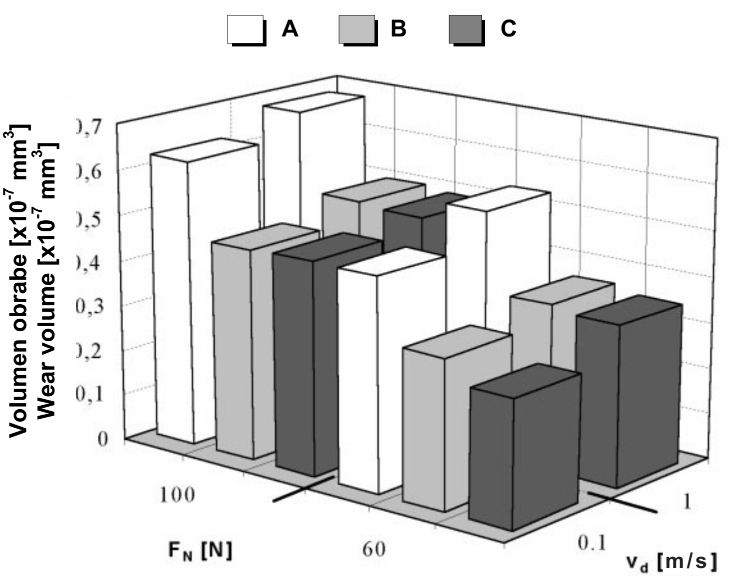
Sl. 6. *Povprečna vrednost koeficienta trenja v odvisnosti od drsne hitrosti in obremenitve*
Fig. 6. *Average coefficient of friction as a function of sliding speed and load*

na 100 N se je tudi koeficient trenja povečal na 0,17, kar je moč pripisati povečanemu številu kovinskih dotikov. Primerjava rezultatov preskušanja pri drsni hitrosti 0,1 in 1 m/s pa ni pokazala nikakršnih razlik v koeficientu trenja, kar je razvidno s slike 6.

Na sliki 7 je prikazana prostornina obrabe kemotermično izboljšanih valjčkov po 2000 m drsenja. V primerjavi s kaljenjem, nitriranje v plazmi ali pulzirajoči plazmi izboljša drsno obrabno odpornost jekla 42CrMo4 ([12], [14] in [15]), ki se je, glede na razmere pri preskušanju, izboljšala celo do 40 odstotkov. Primerjava nitriranja v plazmi ter nitriranja v pulzirajoči plazmi ni pokazala nikakršne razlike v obrabni odpornosti raziskovanega jekla (sl. 7).

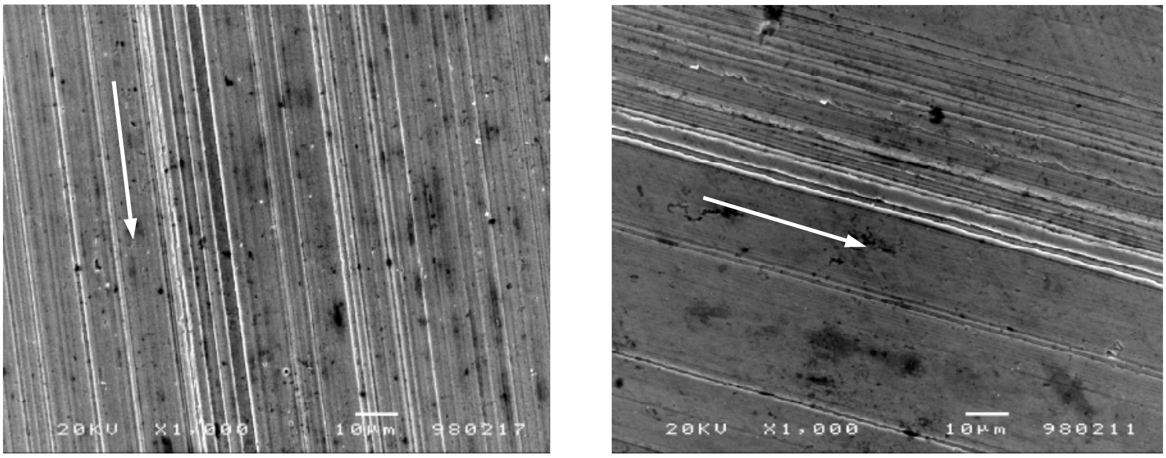
~0.1. Increasing the load (100N) led to a higher coefficient of friction (~0.17), which can be attributed to an increased number of steel-steel contacts. However, no difference in the coefficient of friction could be observed between the two sliding speeds of 0.1 and 1 m/s used (Fig. 6).

Figure 7 shows the wear volume of surface-treated pins as a function of surface treatment, test load and sliding speed after 2000m of lubricated sliding. Depending on the testing conditions, plasma and pulsed-plasma nitriding were found to improve the sliding-wear resistance of 42CrMo4 steel by up to 40% when compared to hardening, which is in agreement with earlier results ([12], [14] and [15]). However, a comparison of plasma and pulsed-plasma nitriding showed no noticeable difference in the wear of the conventional and pulsed-plasma-nitrided pins, as shown in Fig. 7.



Sl. 7. *Prostornina obrabe v odvisnosti od drsne hitrosti in obremenitve*

Fig. 7. *Wear volume of surface-treated pins as a function of sliding speed and normal load*



(a) (b)

Sl. 8. *Obrabljena površina (a) kaljenega valjčka in (b) valjčka, nitriranega v plazmi po drsnem preskusu pri* v_d *= 1 m/s,* F_N *= 60 N, drsna pot 2000m*

Fig. 8. *Worn surface of (a) hardened and (b) plasma-nitrided pin after a lubricated sliding-wear test (*v_s *= 1 m/s,* F_N *= 60 N, sliding distance of 2000m)*

Mikroskopija obrabljenih površin je pokazala, da je bil, ne glede na razmere pri preizkušanju in kemotermično obdelavo površine, prevladujoč obrabni mehanizem, abrazija površine (sl. 8a in 8b).

2.2.2 Preskus jamičenja

Dotikalne napetosti preskušanih zobnikov (točka kotaljenja C) smo izračunali z uporabo Hertzove teorije homogenih elastičnih teles [16], pri čemer smo upoštevali dejanski koeficient trenja, izmerjen na napravi “valjček-plošča” (drsna hitrost 1 m/s in obremenitev 60 N), realno porazdelitev zaostalih napetosti ter dejanski obremenitveni sestav. Ker Hertzova porazdelitev napetosti velja le za homogeno elastično telo, ki ne vsebuje nikakršnih zaostalih napetosti, je pri napetostnem izračunu dejanskih elementov treba upoštevati tudi polje zaostalih napetosti. Pri tem se predpostavlja, da so zaostale napetosti v vzdolžni in obodni smeri enake ($\sigma_{rx} = \sigma_{ry}$), pravokotno na površino pa minimalne, zaradi česar jih lahko zanemarimo ($\sigma_{rz} \approx 0$) [17]. Dejanska porazdelitev dotikalnih napetosti, prikazana na sliki 9, je bila izračunana s superpozicijo zaostalih ter koordinatnih napetosti.

Pri nitriranih zobnikih ležijo največje strižne napetosti, vrednosti $0{,}439 \cdot p_H$, približno 0,12 mm pod površino, torej znotraj nitrirane plasti (sl. 9). Seveda bi bilo treba v primeru močno obremenjenih zobnikov uporabiti daljše čase nitriranja, s čimer bi dosegli večje globine nitriranja ter ustrezno odpornost materiala ([5] in [18]).

Rezultati preskušanja jamičenja so prikazani na sliki 10. V primerjavi s kaljenimi zobniki

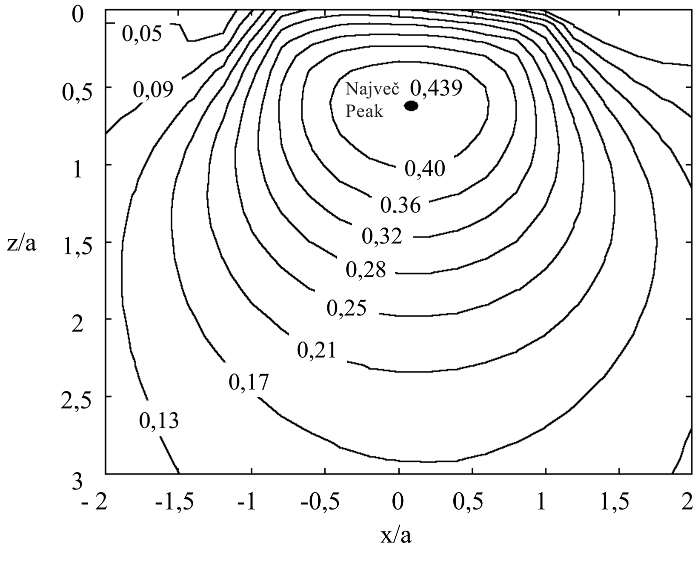
An SEM analysis of the worn surfaces showed that as a result of the boundary lubrication conditions, abrasive wear was the prevailing wear mechanism (Fig. 8a and 8b).

2.2.2 Pitting-wear test

The contact stresses of the testing gears (pitch point C) were calculated using Hertz equations [16], taking into account the coefficient of friction measured on the pin-on-disc machine ($v_s = 1$m/s, $F_N = 60$N), the real distribution of residual stresses as well as the load conditions and the geometry of the testing gears. The Hertz stress distribution of a homogeneous body is only valid when no internal stresses are present in the material, therefore it is absolutely necessary to take into account the residual stresses when calculating the stressing of real machine elements, i.e. gears. Residual stresses in the axial and tangential directions are assumed to be equal ($\sigma_{rx} = \sigma_{ry}$), while the residual stresses normal to the surface are very low when compared to the stresses at the surface, for this reason residual stresses in the *z* direction can be neglected ($\sigma_{rz} = 0$) [17]. Actual stress calculations, shown in Fig. 9, were made by the additive superposition of the residual stresses on the associated coordinate stresses.

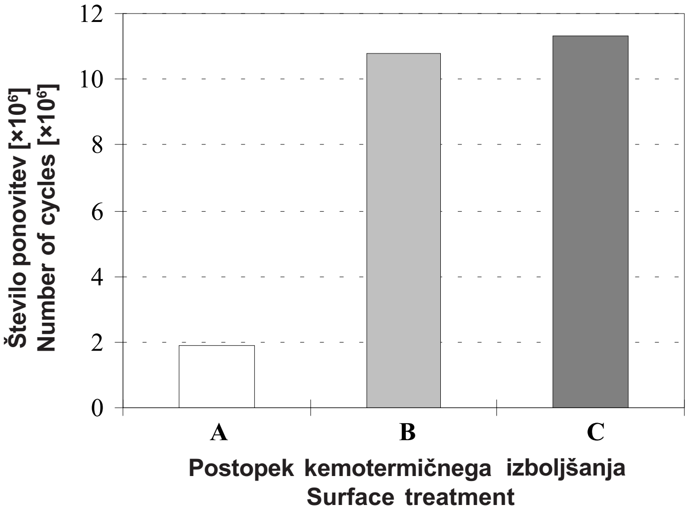
As shown in Fig. 9, the maximum principal shear stresses ($0.439 \cdot p_H$) of plasma-nitrided and pulsed-plasma-nitrided gears are located approx. 0.12 mm below the surface, which is inside the nitrided zone. However, in the case of highly loaded gears longer nitriding times should be used in order to obtain larger nitriding depths and adequate strength of the material ([5] and [18]).

The results of the pitting-wear tests are shown in Fig. 10. Conventional plasma-nitrided and



Sl. 9. *Porazdelitev strižnih napetosti (τ/p_H) pri zobnikih nitriranih v plazmi ($\mu = 0{,}1$, $T = 239{,}3$ Nm, $a_H = 0{,}20$ mm, $p_H = 1125$ MPa)*

Fig. 9. *Principal shear stress distribution (τ/p_H) of plasma-nitrided gears ($\mu = 0{,}1$, $T = 239{,}3$ Nm, $a_H = 0{,}20$ mm, $p_H = 1125$ MPa)*



Sl. 10. *Odpornost proti jamičenju kemotermično izboljšanih zobnikov (razpredelnica 1)*
Fig. 10. *Pitting-wear resistance of surface-treated gears (Table 1)*

imajo zobniki, nitrirani v plazmi ali pulzirajoči plazmi močno izboljšano odpornost proti jamičenju. Poškodba jamičenja se je v primeru kaljenih zobnikov pojavila že po ~ dveh milijonih ponovitev, medtem ko je nitriranje izboljšalo odpornost jekla 42CrMo4 za faktor 5. Kakor v primeru drsne obrabne odpornosti, dajeta nitriranje v plazmi in nitriranje v pulzirajoči plazmi zelo enakovredno odpornost raziskovanega jekla proti jamičenju (sl. 10).

3 OBRAVNAVA

Rezultati preskušanja drsne obrabne odpornosti in odpornosti proti jamičenju kažejo, da nitriranje v plazmi kakor tudi v pulzirajoči plazmi precej izboljšata obrabno odpornost jekla 42CrMo4. V primeru abrazijske obrabe ima trdota površine odločilen vpliv na obrabno odpornost materiala. Za doseganje ustrezne odpornosti proti jamičenju in utrujanju je potrebna primerna kombinacija lastnosti površine in podlage [18]. Izboljšano protiobrabno odpornost jekla 42CrMo4, ki smo jo dosegli z nitriranjem površine, je moč pripisati kombinaciji povečane trdote površine, visokih tlačnih zaostalih napetosti, finozrnate mikrostrukture ter žilavega jedra.

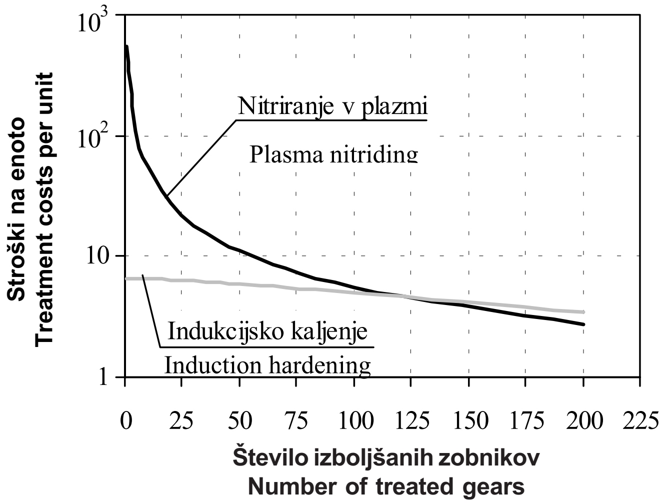
Z namenom narediti celovito primerjavo postopka kaljenja ter nitriranja v plazmi, smo na primeru srednje velikega reduktorja (zunanji premer zobnika 100 mm in širina zob 20 mm), naredili tudi ekonomski izračun oziroma oceno izdelave in zamenjave poškodovanih zobnikov. Slika 11 prikazuje stroške kemotermičnega poboljšanja zobnikov v odvisnosti od uporabljenega postopka in števila izboljšanih zobnikov. Tako v primeru nitriranja kakor tudi indukcijskega kaljenja se stroški izboljšanja zmanjšujejo s številom izboljšanih zobnikov, kar je pričakovano. Pri zelo majhnih serijah so stroški indukcijskega kaljenja precej nižji od stroškov nitriranja v plazmi. S povečevanjem števila izboljšanih zobnikov (>100) pa

pulsed-plasma-nitrided gears show greatly improved pitting-wear resistance when compared to hardened gears. In the case of hardened gears pitting failure occurred after ~2 mio cycles, while nitriding increased the pitting-wear resistance of the 42CrMo4 steel by a factor of 5. As in the case of the sliding-wear tests, plasma nitriding and pulsed-plasma nitriding gives a very similar pitting-wear resistance for the investigated steel, as shown in Fig. 10.

3 DISCUSSION

Sliding- and pitting-wear test results show that plasma nitriding and pulsed-plasma nitriding improve the wear resistance of 42CrMo4 steel. In abrasive wear mechanisms, the surface hardness plays a major role, however, an appropriate combination of surface and subsurface properties are necessary to obtain an appropriate fatigue resistance for the contact surfaces [18]. Therefore, the greatly improved pitting-wear resistance of the nitrided steel can be attributed to a combination of a high surface hardness, a fine surface microstructure, a tough core and high surface compressive stresses.

In order to make a complete comparison between hardened and plasma-nitrided gears, a calculation of the production and replacement costs was carried out on an example of a medium-sized gearbox (gear outer diameter 100 mm and tooth width 20 mm). Figure 11 shows the treatment costs per unit for induction-hardened and plasma-nitrided gears as a function of the number of treated gears. In both cases the treatment costs per unit decrease with the number of treated gears, however, by increasing the number of treated gears to more than 100, plasma nitriding becomes more profitable in comparison with induction hardening (Fig. 11). Another very important cost-saving advantage of the plasma-nitriding pro-



Sl. 11. *Stroški kemotermičnega poboljšanja v odvisnosti od uporabljenega postopka in števila izboljšanih zobnikov*

Fig. 11. *Surface-treatment costs per unit as a function of surface treatment and the number of gears to be treated*

postaja nitriranje v plazmi vedno bolj gospodarno upravičeno (sl. 10). Druga, tudi zelo pomembna lastnost nitriranja v plazmi, ki prav tako pomeni prihranek, je dejstvo, da je z uporabo tehnologije nitriranja v plazmi moč hkrati izboljšati zobnike različnih izmer ([1] in [5]).

Ekonomska primerjava procesa indukcijskega kaljenja in nitriranja v plazmi je temeljila na predpostavki, da je treba zaradi poškodbe jamičenja kaljene zobnike zamenjati vsaj enkrat med dobo trajanja reduktorja. Z upoštevanjem rezultatov preskušanja na napravah "valjček-plošča" in "NPZ" ter stroškov izdelave, izboljšanja in zamenjave zobnikov lahko naredimo naslednjo oceno:

- Pri majhnih serijah (<10 zobnikov) zamenjava postopka indukcijskega kaljenja z nitriranjem v plazmi ekonomsko ne bi bila upravičena. Ker pa so zobniki majhnih serij navadno posebni zobniki, pri katerih pomeni glavni strošek sama izdelava, postane izboljšanje obrabne odpornosti oziroma podaljšanje dobe trajanja zobnika glavni kriterij za izbiro postopka izboljšanja površine.
- V primeru velikih serij (>100 zobnikov) pa pomeni zamenjava indukcijskega kaljenja z nitriranjem v plazmi znižanje stroškov tudi do 100 odstotkov. Prihranek je lahko v primeru močno obremenjenih zobnikov še večji, saj imajo zobniki, nitrirani v plazmi tudi do 5-krat boljšo odpornost proti jamičenju (sl. 10).

4 SKLEPI

- Primerjava jekla 42CrMo4, nitriranega v plazmi in pulzirajoči plazmi, je pokazala zelo podobne vrednosti hrapavosti in mikrotrdote površine po nitriranju ter primerljivo obrabno odpornost.
- Kombinacija velike trdote površine, velikih tlačnih zaostalih napetosti, finozrnate mikrostrukture in

cess is the fact that gears of different sizes and shapes can be treated at the same time ([1] and [5]).

The economic comparison of the induction-hardening and plasma-nitriding processes was based on an assumption that due to pitting failure hardened gears have to be replaced at least once during the lifetime of the gearbox. In addition, an analysis of maintenance procedures in Slovenian companies revealed that in the case of a medium-sized gearbox, the replacement of a gear pair takes approximately 6 hours. By taking into account the results of the pin-on-disc and BGTR tests as well as production and replacement costs, the following evaluation can be made:

- In the case of special, small-series gears (<10) changing from induction-hardened to plasma-nitrided gears may not be profitable. However, in the case of specialised gears, the production of gears represents the main part of the overall costs and therefore the prevention of gear failure represents the main criterion for surface-treatment selection.
- In the case of larger series (>100), a change from induction-hardened to plasma-nitrided gears represents a cost reduction of up to 100%. For highly loaded gears this reduction can be even higher, since plasma nitriding gives up to 5-times better pitting-wear resistance when compared with hardened gears (Fig. 10).

4 CONCLUSIONS

- A comparison of plasma-nitrided and pulsed-plasma-nitrided 42CrMo4 steel shows nearly the same surface roughness and surface microhardness values as well as very similar sliding- and pitting-wear resistance.
- A combination of a high surface hardness, a fine surface microstructure, a tough core and high

žilavega jedra, dobljena z nitriranjem, vodi do ugodnih triboloških lastnosti raziskanega jekla. Rezultati na napravi "valjček-disk" in "NPZ" kažejo, da v primerjavi s kaljenjem, nitriranje v plazmi ter v pulzirajoči plazmi močno izboljša obrabno odpornost jekla 42CrMo4.

- Pri majhnih serijah zobnikov, ki jih je treba izboljšati, je lahko nitriranje v plazmi relativno drag postopek. Kljub vsemu pa zamenjava indukcijskega kaljenja z nitriranjem v plazmi zmanjša verjetnost poškodbe jamičenja, kar vodi do znižanja celotnih stroškov, ki so povezani z zamenjavo zobnikov ter zastojem proizvodnje.

surface compressive stresses, obtained with plasma nitriding, lead to favourable tribological properties of the nitrided steel. Wear-test results show that compared to hardening, plasma nitriding and pulsed-plasma nitriding greatly improve the sliding-wear, and especially the pitting-wear, resistance of 42CrMo4 steel.

- In the case of small series production, the plasma-nitriding process can be rather expensive. However, changing from hardened to plasma-nitrided gears reduces the probability of gear pitting failure and therefore leads to a reduction of the overall costs related to gear replacement and the halting of production.

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