

Preizkušanje vzdržljivosti površin pri kotalno drsnem trenju in majhnih hitrostih

Testing of Surface Endurance in Rolling-Sliding Friction at Low Velocities

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Kotalno-drsni stik je eden od osnovnih načinov, s katerim sta v oprijemu dve površini, poznamo ga pri najrazličnejših sestavah. Še posebej zanimivi so taki stiki, če je proces počasen, ker se v tem primeru mehanizem bistveno razlikuje od hitrih stikov tako po načinu tvorjenja oljnega filma kakor po mehanizmu obrabe. Najbolj značilni so počasni zobiški prenosniki, kakršne uporabljamo npr. pri cementnih mlinih, v naftni industriji, pri prenosnikih za dvigalne naprave itn. Taki počasni zobiški so izpostavljeni procesu obrabe, zaradi česar se spremeni oblika zobiških bokov, s tem pa se poslabšajo kinematicne lastnosti. Ker gre praviloma za večje komponente, je odpravljanje takih napak še težje in dražje. Postopek za dimenzioniranje zobiškov pri takih delovnih razmerah tudi še ni dobro definiran, zato so tovrstne raziskave toliko bolj upravičene.

Ker je zmanjševanje trenja in vsakovrstne obrabe v bistvu pomemben gospodarski problem, so bile v zadnjih desetletjih izvedene in se še vedno izvajajo številne obsežne raziskave obrabe in poškodb površin pri kotalno-drsnih razmerah, predvsem pri večjih hitrostih. Zaradi bistvenih razlik med hitrimi in počasnimi stiki rezultatov teh raziskav ne moremo preprosto ekstrapolirati na naš primer. Pri majhnih hitrostih ima toplota, ki nastane zaradi trenja na površinah, dovolj časa za prenos v okolje in v notranjost. Zato je povišanje temperature zaradi trenja na drsnih površinah pri majhnih hitrostih zanemarljivo, ima pa pri večjih hitrostih pomemben in celo odločujoč vpliv. Prav tako višja temperatura bistveno vpliva na viskoznost mazalnega olja. Debelina oljnega sloja je zelo odvisna od hitrosti drsnih površin. Pri večjih hitrostih je večja, zato je tedaj skoraj vedno obtaja elasto hidrodinamično mazanje, medtem ko prevladuje pri majhnih hitrostih mešano trenje. To so glavni razlogi, da za vrednotenje obrabe pri počasnih drsno-kotalnih stikih ne moremo uporabiti rezultatov, ki veljajo za hitro tekoče. Zato v številnih ustanovah po svetu vlagajo velike napore za oblikovanje ustrezne metode za dimenzioniranje počasnih zobiškov [1] do [5].

Naš začetni cilj je bil ugotavljanje adhezijske obrabe na počasi se gibajočih površinah. V ta namen smo razvili lastno preizkuševališče in izvedli preizkuse na dvojicah iz jeklene litine GS 52 (DIN). Primerljive dvojice pogosto uporabljamo za velike, počasi vrteče se zobiške.

Ključne besede: stik površin, stik kotalno-drsni, prenosniki zobiški, vzdržljivost površin

Rolling-sliding contact is one of the basic ways in which two surfaces are in an interaction; it is present in the most diverse compositions. Such contacts are even more interesting if such a process is slow, because these contacts are essentially different from fast contacts both with regard to oil film building and to wear mechanism. The most characteristic are slow gear trains which are in use, e.g. in cement-mills, in the oil industry, in elevator transmissions, etc. Such slow gears are subjected to a wear process, whose consequence are changes in tooth flank shape and a subsequent deterioration of its kinematic properties. Since they are, as a rule, components of excessive dimensions, their repair is also more laborious and expensive. A rating method for gears operating in such working conditions has not yet been well defined, which is why the necessary research work is even more justified.

Since lowering friction, and any sort of wear, is in its essence an important economic problem, there have been and still are being conducted numerous, extensive investigations of wear and surface damages in rolling-sliding circumstances, particularly at higher speeds. Because of the essential differences between fast and slow contacts we cannot simply extrapolate this research to our case. When velocities are low, heat originating in surface friction has enough time for being conveyed into the surround and into the substrate. That is why the rise of temperature caused by friction on sliding surfaces at low velocities is negligible, but it has an important or even prevailing influence when velocities are higher. A higher temperature substantially influences the lubricating oil film viscosity as well. The oil film thickness is strongly dependent on the velocity of the sliding surfaces. It becomes thicker with higher velocities, therefore in such case there usually exists an elasto-hydrodynamic lubrication, whereas at low velocities a mixed lubrication prevails. These are the main reasons why, for evaluation of wear in slow sliding-rolling contacts, we cannot use results which are valid for fast contacts. Hence, new efforts are being made to form an adequate rating method for slow running gears [1-5] in numerous institutions all over the world.

Our starting goal was to describe existence of adhesive wear on slowly running surfaces. For this purpose we developed our testing arrangement and conducted experiments with disk pairs made of cast steel GS 52 (DIN). Comparable pairs are often used for large, slowly running gears.

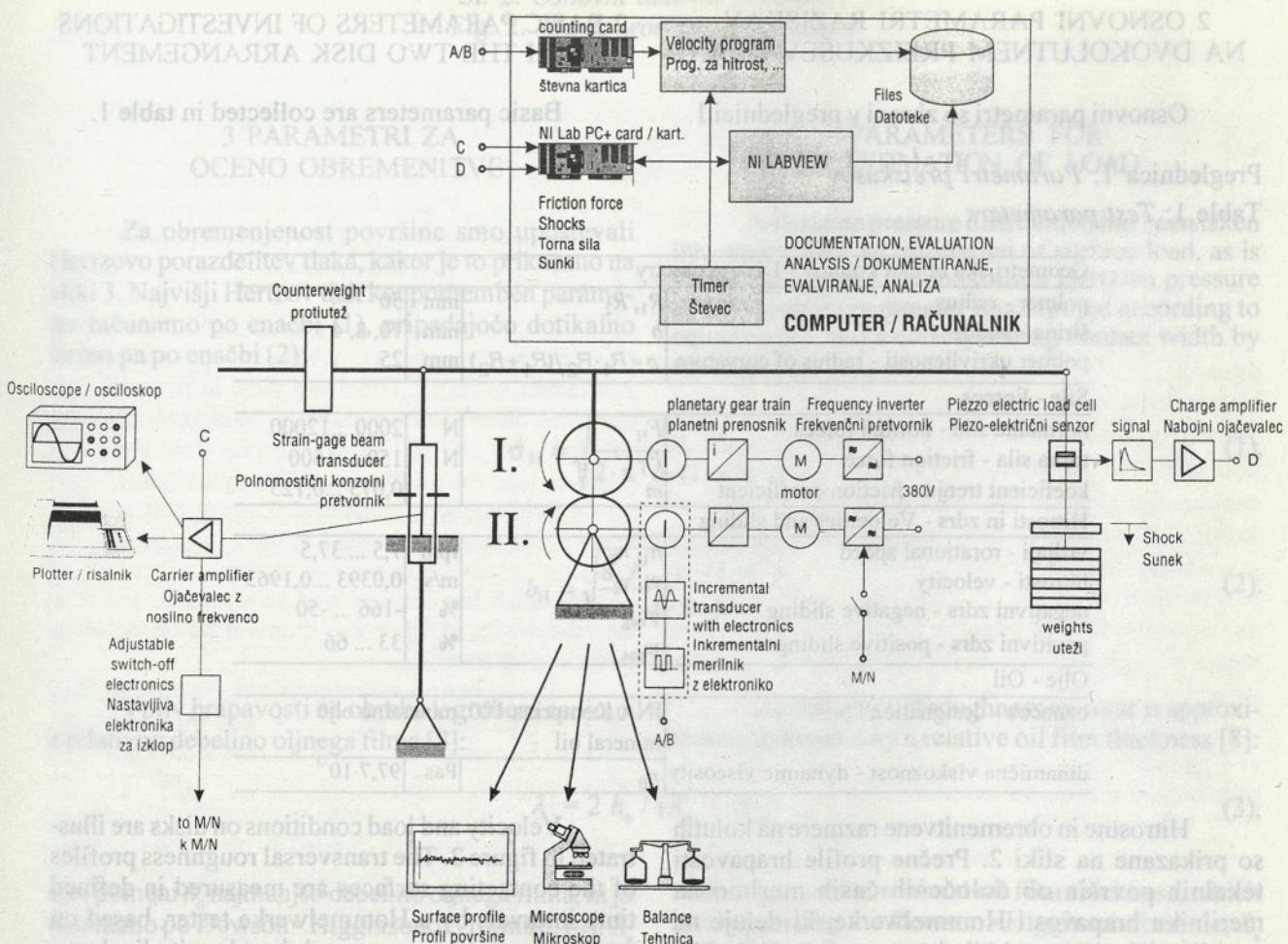
Keywords: surface contact, rolling sliding contact, gear trains, surface endurance

1 ZASNOVA IN NAČELO DELOVANJA PREIZKUŠEVALIŠČA

Osnovna shema dvokolutnega preizkuševališča je prikazana na sliki 1. Naprava ima dva koluta: spodnjega na nosilnem delu ogrodja in zgornjega na obremenilnem vzvodu. Vsak kolut je nameščen na svojem vretenu, ki ga prek planetnega prenosnika poganja lasten motor. Hitrosti motorjev spremojamo s frekvenčnima pretvornikoma in ju merimo z inkrementalnimi meritnikoma. Signal registrira posebna števna kartica, hitrost pa potem računamo s posebnim računalniškim programom. Normalno obremenitev uravnavamo z utežmi, ki so obešene na enem koncu vzvoda v razmerju 1:5. Vzvod je na drugem koncu prek dolge mahalke opri na ogrodje ter uravnotežen s protiutežjo. Mahalka je v višini dotikalisa kolutov vodoravno oprita na togo merilno polno-mostičkovno konzolo.

1 CONCEPT AND WORKING PRINCIPLES OF THE TESTING ARRANGEMENT

A basic scheme of the two-disk testing arrangement is shown in figure 1. The device has two disks, a lower one mounted on the carrying part of a framework and an upper disk on a loading lever. Each disk is mounted on a separate spindle, which is powered via a planetary gear train by its motor. Motor speeds can be controlled by frequency inverters and measured by incremental transducers. Their signal is registered by a special counting card, and the velocity is then computed by a real time computer program. A normal load is settled by weights, which are hung at the longer end of a lever with the ratio 1:5. The opposite side of the lever is supported on the framework through an intermediary long waver. The waver is supported on a stiff full-bridge measurement beam transducer at the height of the disk contact point.



Sl. 1. Shema preizkuševališča
Fig. 1. Scheme of the testing arrangement

Oba zgiba mahalke, med vzdodom in med ogrodjem, sta izvedena s kotalnimi ležaji, tako da je trenje čim manjše, s tem pa je zmanjšan tudi vpliv na odstopek merjene sile trenja. Ta odstopek je odvisen od dolžine mahalke in je toliko manjši, kolikor večja je njena dolžina. Izmerjeno silo trenja lahko opazujemo na osciloskopu, lahko jo registriramo na laboratorijskem risalniku Hewlett Packard, lahko pa jo prek ustreznih laboratorijskih kartic opazujemo ali zapisemo in obdelamo z računalnikom. Z zaznavalom dolžine - LVDT zaznamo tudi navpično nihanje vzdoda, ki nastane zaradi neokroglosti oziroma izsrednosti preizkušancev. Med utežjo in vzdodom je nameščeno piezoelektrično zaznavalo, s katerim lahko raziskujemo sunkovite preobremenitve dotikalnih površin. Naprava je opremljena z elektroniko za izklop pogonov ob preobremenitvi. To je potrebno, če pride do nenadnega povečanja torne sile zaradi zajedanja površin. Na preprost način lahko zbiramo obrabne delce, po katerih lahko potem sklepamo o vzrokih poškodb. Mazanje je izvedeno s posebno črpalko, ki dovaja olje na vrh zgornjega kolata.

2 OSNOVNI PARAMETRI RAZISKAV NA DVOKOLUTNEM PREIZKUŠEVALIŠČU

Osnovni parametri so zbrani v preglednici 1.

Preglednica 1: Parametri preizkusov

Table 1: Test parameters

Geometrijska oblika kolutov - Disk geometry				
polmer - radius	R_1, R_2	mm	50	
širina - width	b	mm	10, 8, 4	
polmer ukrivljenosti - radius of curvature	$\rho = R_1 \cdot R_2 / (R_1 + R_2)$	mm	25	
Sile - Forces				
normalna sila - normal forces	F_N	N	2000 ... 12000	
torna sila - friction force	F_T	N	150 ... 1500	
koeficient trenja - friction coefficient	m		0,075 ... 0,125	
Hitrosti in zdrs - Velocities and sliding				
vrtljaji - rotational speed	n_1, n_2	rpm	7,5 ... 37,5	
hitrosti - velocity	v_1, v_2	m/s	0,0393 ... 0,1963	
negativni zdrs - negative sliding	ψ_{neg}	%	-166 ... -50	
pozitivni zdrs - positive sliding	ψ_{pos}	%	33 ... 66	
Olje - Oil				
oznaka - designation	INA Komprina 100, mineralno olje - mineral oil			
dinamična viskoznost - dynamic viscosity	η_0	Pas	$97,7 \cdot 10^{-3}$	

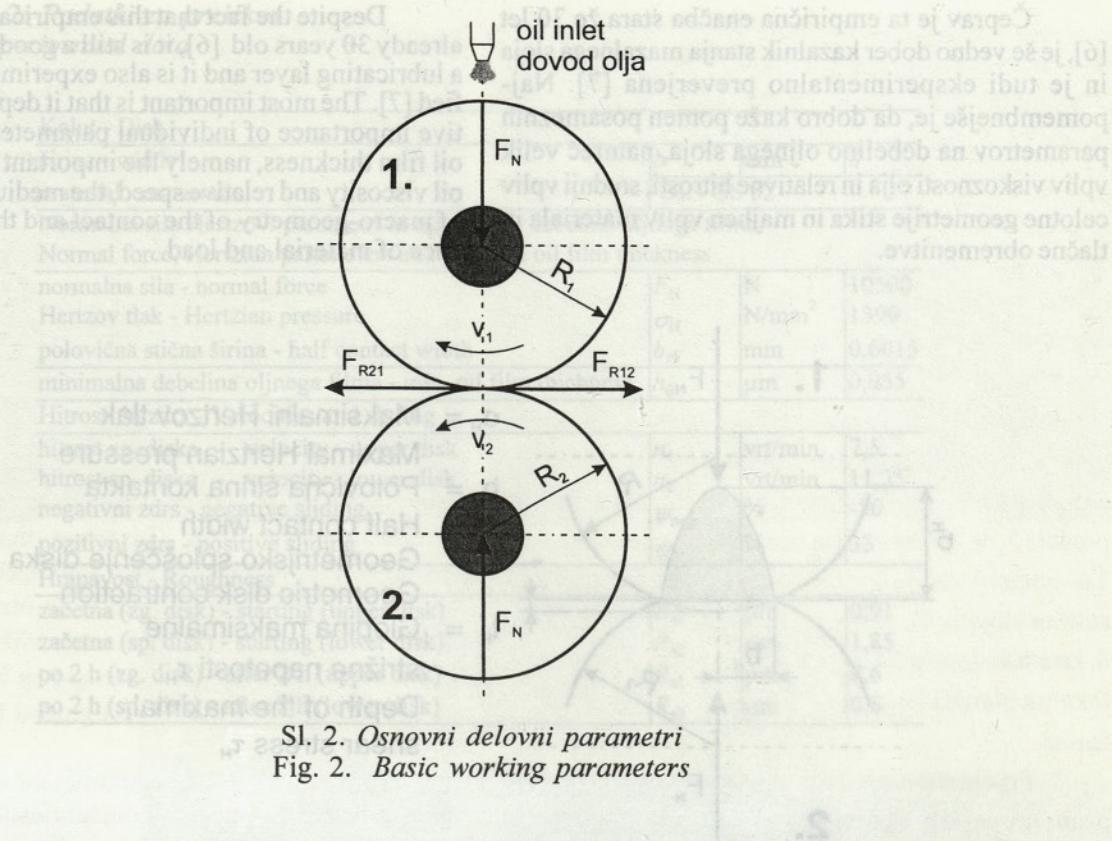
Hitrostne in obremenitvene razmere na kolutih so prikazane na sliki 2. Prečne profile hrapavosti tekalnih površin ob določenih časih merimo na merilniku hrapavosti Hommelwerke, ki deluje na temelju električnega dotikalnega zaznavala, kratke vzdolžne segmente v istih tekalnih časih pa z merilnikom TalySurf. Mase kolutov smo ugotovljali s tehtanjem na Mettlerjevi analitski tehtnici.

Both joints of the waver – the one on the lever side and the other on the framework – are equipped with roller bearings to keep friction as low as possible, thus also lowering influence on the deviation of a measured friction force. This deviation depends on the length of the waver: the smaller it is, the greater the length. The measured friction force can be observed by an oscilloscope, it can be registered on Hewlett Packard lab-plotter, and it can be detected by a proper laboratory computer card and recorded and analyzed by a computer. An LVDT sensor also registers vertical movements of the lever, which emerge because of the roundness error or eccentricity of samples. A piezzo-electric load cell, which enables observation of overloads of the contacting surfaces caused by shocks, is mounted between the weights and the lever. The device is equipped with switch-off electronics in case of an overload. It is necessary to switch off drives if there occurs an instantaneous increase in the friction force because of scuffing. We can sample wear particles in a simple way, and on this basis determine the reasons for the damage. Lubrication is carried out by a special pump, which supplies oil to the top of the upper disk.

2 BASIC PARAMETERS OF INVESTIGATIONS WITH THE TWO DISK ARRANGEMENT

Basic parameters are collected in table 1.

Velocity and load conditions on disks are illustrated in figure 2. The transversal roughness profiles of the contacting surfaces are measured in defined time intervals by a Hommelwerke tester, based on an electric contact sensor, and short longitudinal segments in the same time segments by TalySurf equipment. The disk mass has been settled by weighing with a Mettler analytical balance.



Sl. 2. Osnovni delovni parametri
Fig. 2. Basic working parameters

3 PARAMETRI ZA OCENO OBREMENITVE

Za obremenjenost površine smo upoštevali Hertzovo porazdelitev tlaka, kakor je to prikazano na sliki 3. Najvišji Hertzov tlak kot pomemben parameter računamo po enačbi (1), pripadajočo dotikalno širino pa po enačbi (2):

$$\sigma_H = \sqrt{\frac{F_N \cdot E}{2 \cdot \pi \cdot b \cdot (1 - v^2) \cdot \rho}} \quad (1),$$

$$b_H = \sqrt{\frac{8 \cdot F_N \cdot \rho \cdot (1 - v^2)}{b \cdot \pi \cdot E}} \quad (2).$$

Vpliv hrapavosti na obrabo v grobem cenimo z relativno debelino oljnega filma [8]:

$$\lambda = 2 h_0 / (R_{a1} + R_{a2}) \quad (3),$$

kjer pomeni h_0 najmanjšo debelino oljnega filma, ki jo računamo po Dowson - Higginsonovi formuli, (4). R_a je srednji aritmetični odstopek profila, medtem ko je:

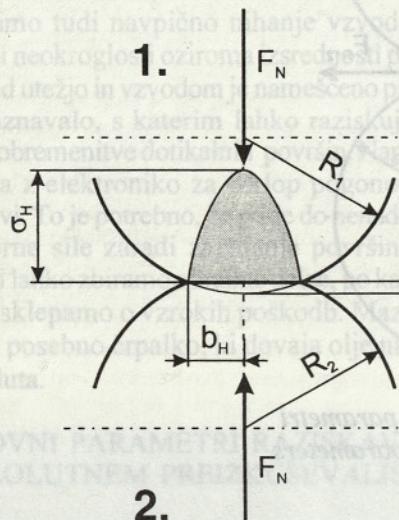
$$h_0 = 2,65 \alpha^{0,54} (E')^{-0,03} \eta_0^{0,7} u^{0,7} \rho^{0,43} w^{0,13} \quad (4).$$

The influence of roughness on wear is approximately estimated by a relative oil film thickness [8]:

where h_0 means a minimal oil film thickness, which is computed by the Dowson - Higginson formula, R_a is the central line average of a profile, while:

Čeprav je ta empirična enačba stara že 30 let [6], je še vedno dober kazalnik stanja mazalnega sloja in je tudi eksperimentalno preverjena [7]. Najpomembnejše je, da dobro kaže pomen posameznih parametrov na debelino oljnega sloja, namreč velik vpliv viskoznosti olja in relativne hitrosti, srednji vpliv celiotne geometrije stika in majhen vpliv materiala in tlačne obremenitve.

Despite the fact that this empirical equation is already 30 years old [6], it is still a good indicator of a lubricating layer and it is also experimentally verified [7]. The most important is that it depicts the relative importance of individual parameters regarding oil film thickness, namely the important influence of oil viscosity and relative speed, the medium influence of macro-geometry of the contact and the low influence of material and load.



Sl. 3. Hertzov stik
Fig. 3. Hertzian contact

4 PREIZKUS S PREKINJENIM MAZANJEM

Ta preizkus je dal oceno časa, ki je potreben, da se oljni film na počasnih mazanih površinah razkroji. Najprej so se koluti utekvali do tiste mere, ko se je sila trenja ustalila, nato pa smo dotok olja za mazanje ustavili. Po določenem času obratovanja pri enakomerni obremenitvi se je oljni sloj na površini razkrojil in prišlo je do hladnega zajedanja. Pri tem se je sila trenja zelo hitro zvečevala. Elektronika za izklop je bila nastavljena na 1,5-kratno imensko vrednost, kar se je izkazalo kot ustreznata vrednost za ustavljanje naprave v primerem trenutku za opazovanje nastalih zajed.

Podatki o preizkušanju so zbrani v pregledni ci 2. Hrapavost površin je bila merjena pred pričetkom preizkusa in nato ponovno po dveh urah obratovanja.

Silo trenja smo zaznavali ves čas trajanja preizkusa, to je 153 min, in jo posneli na risalnik. Najpomembnejši deli tega zapisa so prikazani na sliki 4. Točka A pomeni začetek preizkusa (zapisa), v točki B je bil po 131. minutni obratovanja ustavljen dotok olja, v točki K sta se pa površini zajedli in oba motorja sta se ustavila (konec preizkusa). Koluta sta obratovala brez olja 22 min.

- | | |
|------------|---|
| σ_H | = Maksimalni Hertzov tlak |
| | Maximal Hertzian pressure |
| b_H | = Polovična širina kontakta |
| f | = Geometrijsko sploščenje diska |
| | Geometric disk contraction |
| t_H | = Globina maksimalne strižne napetosti τ_H |
| | Depth of the maximal shear stress τ_H |

Basic parameters are collected in table 1.

4 EXPERIMENT WITH A LUBRICATION CUT-OFF

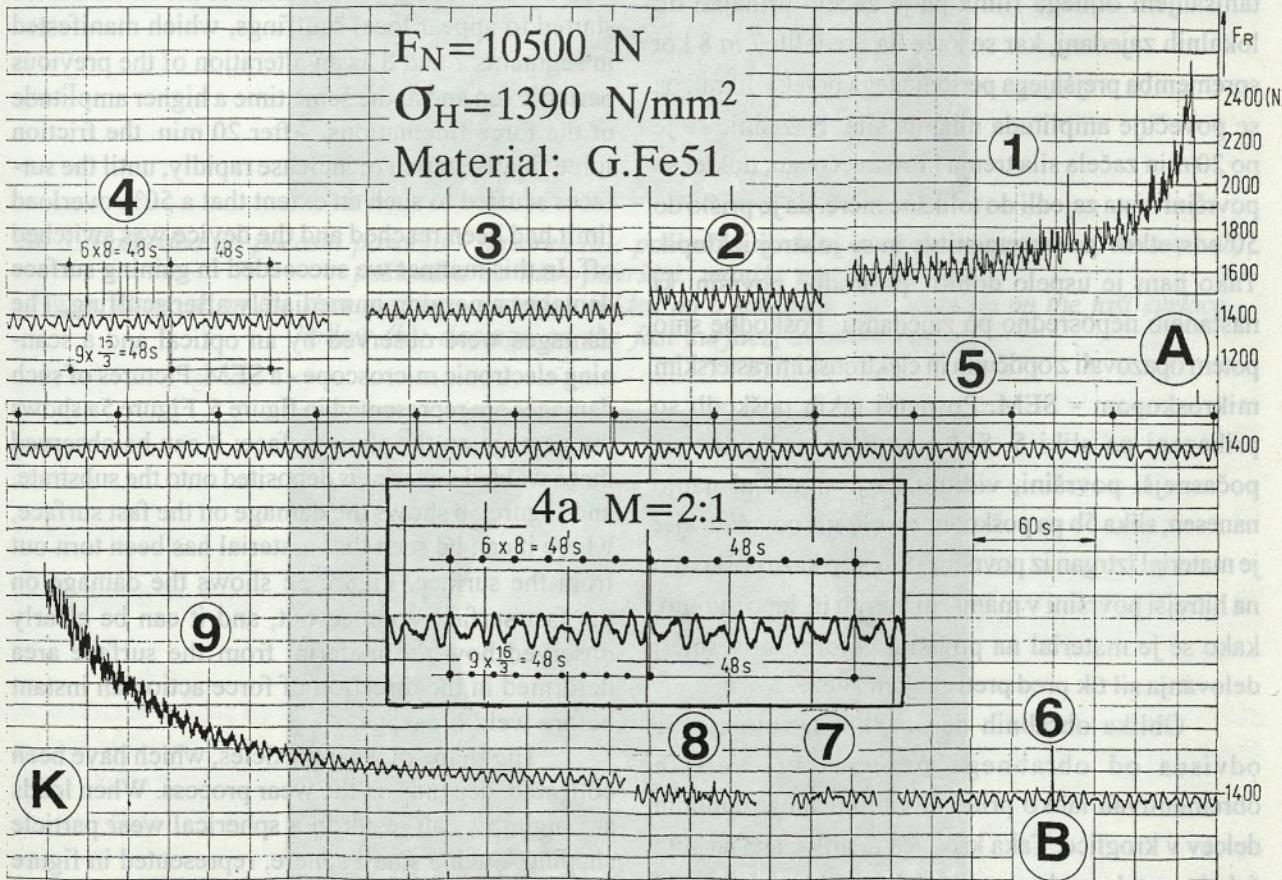
This experiment gave us an estimation of the time, necessary to deteriorate the oil film of the slow lubricated surfaces. The disks were at first run into the state when the friction force stabilized, then the oil flow was cut off. After a certain time span at a uniform load the oil film on the surfaces deteriorated and a cold scuffing appeared. During this process the friction force increased rapidly. The switch off electronics was set to the 1.5 multiple of a nominal value, which has been proved as a suitable value to stop the device at the proper moment for observation of emerging scuffings.

The experimental conditions are presented in table 2. The surface roughness was measured before the experiment and then repeated after two working hours.

The friction force was registered continuously during the experiment, that is 153 min, and recorded on the plotter. The most important segments of this recording are shown in figure 4. The point A corresponded to the start of the experiment (recording); the oil flow was cut off at point B after 131 working minutes; at point K both surfaces scuffed and the motors stopped (end of the experiment). The disks ran without oil for 22 min.

Preglednica 2: Podatki za preizkus
Table 2: Experimental data

Kolut - Disk			
širina - width	b	mm	8
material - material	DIN GS 52		
Normalna sila Hertzovi parametri in minimalna debelina oljnega filma			
Normal force, Hertzian parameters and minimal oil film thickness			
normalna sila - normal force	F_N	N	10500
Hertzov tlak - Hertzian pressure	σ_H	N/mm ²	1390
polovična stična širina - half contact width	b_H	mm	0,6015
minimalna debelina oljnega filma - min. oil film thickness	h_0	µm	0,055
Hitrosti in zdrs - Velocities and sliding			
hitrost zg. diska - velocity - upper disk	n_1	vrt/min	7,5
hitrost sp. diska - velocity - lower disk	n_2	vrt/min	11,25
negativni zdrs - negative sliding	ψ_{neg}	%	-50
pozitivni zdrs - positive sliding	ψ_{pos}	%	33
Hrapavost - Roughness			
začetna (zg. disk) - starting (upper disk)	R_{a1}	µm	0,91
začetna (sp. disk) - starting (lower disk)	R_{a2}	µm	1,85
po 2 h (zg. disk) - after 2 h (upper disk)	R_{a1}	µm	0,6
po 2 h (sp. disk) - after 2 h (lower disk)	R_{a2}	µm	0,6



Sl. 6. Obrazec poteka sile trenja v pogonico
Fig. 6. Wear pattern of a small sphere

Predeli 1 do 3 pomenijo fazo utekavanja, ki je trajala približno dve uri. Predela 4 in 5 pomenita že umirjeno obratovanje in lahko opazimo, da je spremjanje sile trenja periodično. Po vsakem šestem vrtljaju zgornjega koluta in vsakem devetem vrtljaju spodnjega koluta prideta oba koluta do stika na istem mestu kotalnih površin. To je v večjem merilu prikazano na detajlu slike 4a. Nihanje sile trenja je posledica spremjanja lastnosti kotalnih površin na vsakokratnem mestu dotika. Če opazujemo spremjanje sile trenja znotraj posameznih periodov vidimo, da se oblike posameznih nihajev spreminjajo. Ko je utekavanje končano, kar razberemo npr. iz predela 5, se oblika zapisa bistveno ne spreminja več. To pomeni, da se je obraba ustalila, seveda z mazalnim slojem. To trditev potrjujeta tudi predela 7 in 8, ko sta koluta tekla brez mazanja in se že pojavljajo lokalna manjša zajedanja, kar je razvidno iz oblike zapisa.

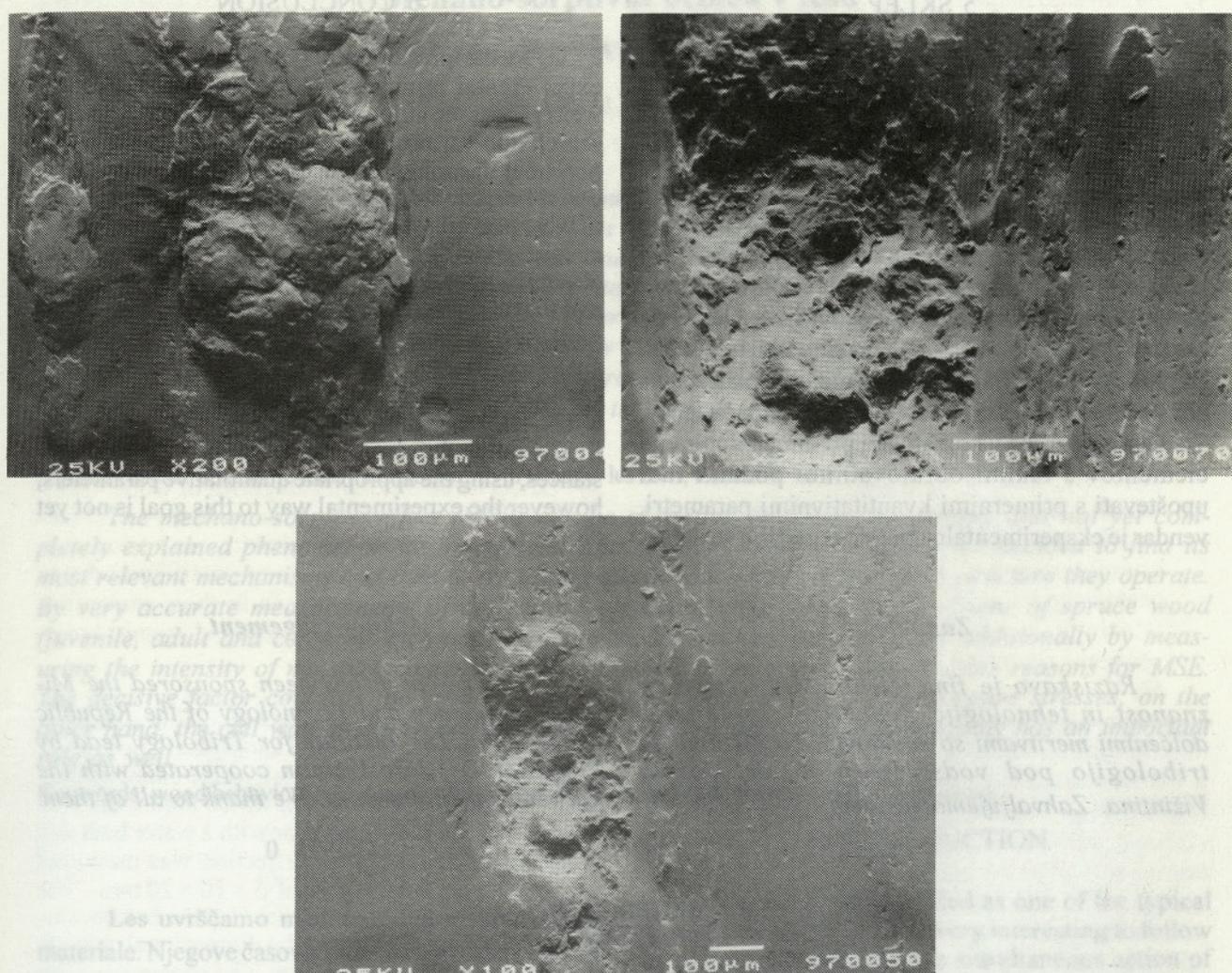
Pri obratovanju brez mazanja v začetku ni bilo pomembnejših sprememb sile trenja. Hkrati s tanjšanjem oljnega filma pa je začelo prihajati do lokalnih zajedanj, kar se kaže na predelih 7 in 8 kot sprememba prejšnjega periodičnega poteka, hkrati pa se povečuje amplituda nihanja sile. Nazadnje se je po 20 min začela sila trenja hitro zvečevati, dokler se površini nista zajedli do tolikšne mere, da je prišlo do 50 odstotkov preobremenitve in se je stroj izklopil. Tako nam je uspelo dobiti poškodbe površin, ki nastanejo neposredno po zajedanju. Poškodbe smo potem opazovali z optičnim in elektronskim rasterskim mikroskopom - SEM. Posnetki takih poškodb so prikazani na sliki 5. Slika 5a kaže poškodbo na počasnejši površini, vidimo da je material nanjo nanesen, slika 5b pa poškodbo na hitrejši površini, kjer je material iztrgan iz površine. Slika 5c kaže poškodbo na hitrejši površini v manjšem merilu in lepo vidimo, kako se je material na površini deformiral v smeri delovanja sil tik pred pretrganjem zvezze.

Oblika obrabnih delcev, ki jih zbiramo, je odvisna od obrabnega procesa. Pri velikih obremenitvah lahko pride do oblikovanja obrabnih delcev v kroglice. Taka kroglica je prikazana na sliki 6, ki je nastala med enim od naših preizkusov pri veliki obremenitvi.

Segments 1 to 3 represent a running-in phase, which took about two hours. Segments 4 and 5 represent a smooth operation, and we can observe that the friction force fluctuations are periodic. After each 6th revolution of the upper disk and each 9th revolution of the lower disk both disks come into contact, appearing at the same spot of the rolling surfaces. This is shown zoomed in the detail of Figure 4a. The friction force fluctuations are a consequence of the changing properties of the rolling surfaces at individual contact points. If we follow the friction force fluctuations inside individual periods, we can observe the changes of individual oscillations. When the running-in phase is finished – as it can be read, e.g. from the segment 5 – the shape of the readings does not change substantially. This means that the wear in presence of the lubricating film stabilizes. This statement could be also confirmed from observing segments 7 and 8, when the disks ran without lubrication and there already started to appear local smaller scuffings, which could be recognized from the recording.

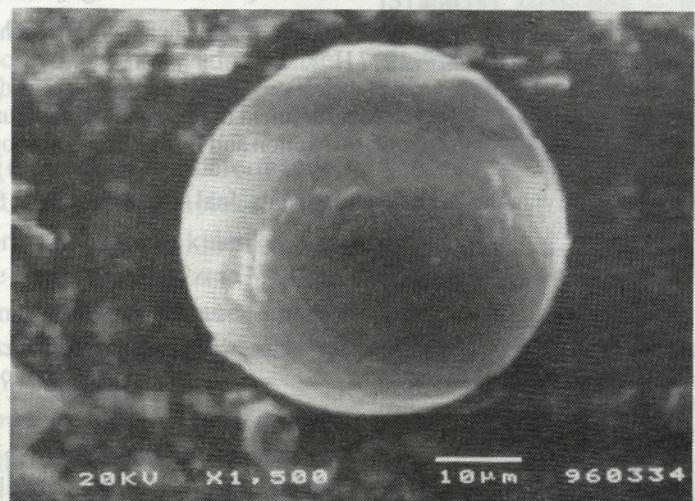
At first there were no significant friction force changes when operating without lubrication. Together with the increasing deterioration of the oil film there started to appear local scuffings, which manifested in segments 7 and 8 as an alteration of the previous periodic run and at the same time a higher amplitude of the force fluctuations. After 20 min. the friction force finally started to increase rapidly, until the surfaces scuffed to such an extent that a 50% overload limit had been reached and the device was switched off. In this manner we succeeded in gaining surface damages emerging immediately after scuffing. The damages were observed by an optical and a scanning electronic microscope - a SEM. Pictures of such damages are represented in figure 5. Figure 5a shows the damage on the slow surface; it can be observed that a welded material is deposited onto the substrate, and Figure 5b shows the damage on the fast surface, where it can be seen that material has been torn out from the surface. Figure 5c shows the damage on the fast surface zoomed out, and it can be clearly observed how the material from the surface area deformed in the direction of force action an instant before weld breakage.

The shape of wear particles, which have been collected, depends on the wear process. When loads are high this can result in a spherical wear particle shaping. Such a small sphere, represented in figure 6, arose during one of our experiments with a high load.



Sl. 5. Poškodba na počasni površini - navarek (a); poškodba na hitri površini - iztrganina, kotanja (b); poškodba na hitri površini, manjše merilo (c)

Fig. 5. Damage on the slow surface - material welded on a substrate (a); damage on the fast surface - hollow (b); damage on the fast surface, zoomed out (c)



Sl. 6. Obrabni delec, preoblikovan v kroglico
Fig. 6. Wear particle transformed into a small sphere

5 SKLEP

V prispevku smo opisali preizkuševališče za raziskovanje obrabnih procesov pri majhnih hitrostih, ki omogoča raziskavo različnih obrabnih pojavov v tem območju. Preizkus, ki smo ga opisali v tem prispevku in smo ga nekajkrat ponovili, naj bi odgovoril na vprašanje o prevladujoči vrsti obrabe pri mazanih katalno-drsnih stikih pri majhnih hitrostih. Izkazalo se je, da je v takih razmerah prevladujoča obraba zaradi utrujanja površin in je hkrati zanemarljiva adhezivna obraba. S hkratnimi raziskavami smo tudi ugotovili, da se zaradi ponavljanja se obremenitve material na površini utrdii in zato spremeni svoje fizikalne lastnosti. To dejstvo je treba v končni fazi pri dimenzioniranju elementov s takimi obratovalnimi podatki tudi upoštevati s primernimi kvantitativnimi parametri, vendar je eksperimentalna pot do tega cilja še dolga.

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5 CONCLUSION

In the present paper we have described the experimental arrangement for an investigation of wear processes at low velocities, which enables research into various phenomena in this area. The experiment described in this paper, and repeated several times, should answer the question of which type of wear prevails in lubricated rolling-sliding contacts at low velocities. It has been proven, that in such circumstances there prevails wear caused by fatigue and that at the same time the adhesive wear is negligible. With parallel investigations we also ascertained a surface material hardening caused by an intermittent load and a consequent change of its physical properties. This fact must be taken into account when finally rating the elements operating in such circumstances, using the appropriate quantitative parameters; however the experimental way to this goal is not yet close.

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