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Primeri fretinga* v sodobnih strojih in napravah

Occurance of Fretting in Modern Devices and Machinery

Mitjan Kalin - Jože Vižintin

Freting se lahko pojavlja v vseh primerih, kjer so stiki izpostavljeni vibracijam, spreminjanju napetostno-deformacijskega stanja, ki omogoča relativne pomike, termičnim spremembam idr. Že relativni pomiki približno 0,1 μm lahko povzročijo porušitev elementa zaradi fretinških poškodb, kar pomeni, da je freting zelo težko v celoti odpraviti. V prispevku so predstavljeni nekateri značilni primeri, kjer prihaja do fretinških poškodb. Ker pa se v novejšem času v strojih vse pogosteje uporabljajo visoko zmogljive keramične komponente, je vse več primerov fretinških poškodb na spojih med keramiko in jeklom. Zato so predstavljeni tudi najpogostejši primeri, pri katerih se freting pojavlja v nosilnih dotikih med jeklom in keramiko iz silicijevega nitrida.

(Ključne besede: freting, jekla, keramika, nitridi silicijevi)

Fretting conditions are found in practically any technical system where contact vibrations are present, or where the contact stresses are induced by cyclic accelerations, fatigue stresses, acoustical noise or temperature variations, thus enabling small relative motion. It is known that even reciprocating movements as short as 0,1 μm in amplitude can cause failure of a component. This means that fretting is very difficult to completely prevent. Recently, high performance ceramics are increasingly used in modern machinery. Consequently, more frequent occurrences of fretting between the ceramics and steel - the prevailing engineering material - are expected. The ceramic material which is used most frequently in applications where fretting could occur is silicon nitride, and therefore it deserves the most attention. In this paper, the most common applications where fretting occurs between the steel and silicon nitride ceramics are presented.

(Keywords: fretting, steel, ceramics, silicon nitride)

0 UVOD

V vseh primerih, pri katerih so površine v stiku izpostavljene vibracijam ali spreminjanju napetostnega stanja, tako da so mogoči majhni relativni premiki med njimi, obstaja možnost nastanka fretinških poškodb. Tudi pomiki, ki dosegajo amplitude le do 0,1 μm, lahko povzročijo fretinške poškodbe in s tem okvaro posameznega dela, znano pa je, da vmesni prilegi med strojnimi elementi omogočajo pomike približno do 1 μm [1]. Ker je tako majhne pomike težko popolnoma odpraviti, je verjetnost nastanka fretinških poškodb v strojih in napravah izjemno velika. Pri tem lahko prihaja do poškodbe utrujanja z značilnimi utrujenostnimi razpokami ali do obrabe, ki vključuje različne mehanizme, odvisno od materialov, okolice in razmer v stiku, npr.: napetosti, hitrosti, frekvenc nihanja, amplitud pomika idr. Čeprav freting že zelo dolgo raziskujejo, razpoznavajo, odkrivajo in iščejo mogoče rešitve za njegovo odpravo, je pregled tega področja pokazal, da se število primerov pojavljanja fretinga v praksi ne zmanjšuje [2]. Tudi najnovejša raziskava pojavljanja fretinških poškodb v jedrskih elektrarnah

0 INTRODUCTION

Fretting conditions are found in practically any technical system where contact vibrations are present, or where the contact stresses are induced by cyclic accelerations, fatigue stresses, acoustical noise or temperature variations, thus enabling small relative motion. It is clear that the probability of encountering fretting in machines and engineering structures is extremely high. It is known that even reciprocating movements as short as 0,1 μm in amplitude can cause failure of a component and that interference fits in machine parts allow sliding on the scale of about 1 μm [1]. Therefore, it is very difficult to eliminate such small movements and, consequently, the resultant fretting. Fretting wear and fretting fatigue are present in almost all machinery and are the cause of total failure of some otherwise robust components. Surveys reveal that, unlike other forms of wear, the incidence of fretting problems in machinery has not declined over the past decades [2], in spite of many years of recognising and studying fretting damage. Moreover, the latest research on fretting damage in

* Poleg izraza "freting" se lahko uporablja tudi izraz "torna obraba", ki ga je poznal že prof. Struna, nekdanji predsednik Terminološke komisije pri SAZU, pri svojem predmetu Teorija trenja, obrabe in mazanja. (Op.ured.)

na Kitajskem je pokazala, da pojav fretinga v zadnjih desetletjih ne upada [3].

V zadnjih letih se uveljavlja veliko novih materialov, med njimi inženirska keramika, imenovana tudi visoko zmogljiva keramika. Visoko zmogljiva keramika so materiali, ki imajo eno ali več izjemnih lastnosti, ki jih dosežejo s posebnimi postopki obdelave surovin in vrhunskimi procesnimi tehnikami. Poleg tega se zanje praviloma uporabljajo kemično sintetizirane osnovne surovine. Uporaba keramike v sodobnih napravah se hitro zvečuje, ker se njena kakovost in zanesljivost močno povečujeta, hkrati pa se cena znižuje. To pomeni, da lahko v prihodnje pričakujemo večjo pojavnost fretinga med keramičnimi in jeklenimi komponentami, ki so pa še vedno najpogostejše v strojnih napravah. Poznavanje obrabnih mehanizmov v teh sistemih je ključnega pomena za odpravljanje in preprečevanje neželenih poškodb.

V tem prispevku so predstavljena najbolj značilna industrijska področja, ki uporabljajo keramične komponente v napravah, pri katerih so možnosti za pojav fretinga velike.

1 PRIMERI POJAVLJANJA FRETINŠKIH POŠKODB

V številnih publikacijah so opisani primeri pojavljanja fretinških poškodb ali možnosti za njihov nastanek v praktično vsakem mehanskem spoju, ki omogoča "majhne" premike. Če je vsaj ena površina v stiku izpostavljena še cikličnim obremenitvam, je verjetnost za nastanek fretinškega utrujanja še večja. V literaturi [4] je opisanih nekaj najpomembnejših strojev oziroma sistemov, pri katerih se freting pojavlja. Nekateri med njimi so predstavljeni v preglednici 1. Poleg teh pa so podani še deli strojnih elementov na primeru letala, ki so zelo izpostavljeni fretingu [5]. Seznam potencialnih fretinških poškodb je seveda precej daljši, vendar ga lahko skrčimo le na določene vrste strojnih elementov, kakor so sklopke, ležaji, različni spoji idr.

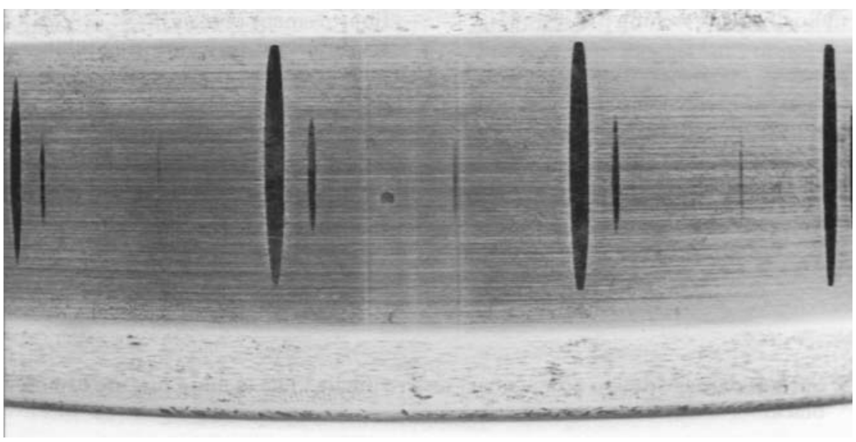
Chinese nuclear power plants has shown that fretting damage is far from decreasing [3].

In recent years many new materials are being used in various engineering applications, such as high performance ceramics. High performance ceramics are materials where one or more properties have been developed to a high degree through specialised treatment of the raw materials and through highly developed processing techniques. In addition, synthetically manufactured raw materials are most commonly used. Since the quality and reliability of ceramics increase continues to while the cost decreases, the use of ceramics in modern machinery has grown in recent years. Therefore, an increase in occurrence of fretting between steel, as the prevailing material in engineering structures, and ceramics should be expected. Knowledge about the wear mechanisms in these systems is therefore crucial for better prevention of undesirable damage.

In this paper, the most typical industrial areas where ceramics could be applied as different components in machinery, and where a strong possibility of fretting damage exists, are presented.

1 APPLICATIONS WHERE FRETTING DAMAGE OCCURS

Numerous publications have documented the occurrence of fretting or the potential occurrence of fretting in any mechanically fastened joint or in surfaces in contact under small relative motion. In addition, one or both of the contacting surfaces are subject to cyclic loading then one or both of the members may experience fretting fatigue. Reference [4] lists many specific components where fretting occurs. Some are in the systems presented in Table 1. In addition, examples of aircraft components prone to fretting damage are given in Table 1 [5]. The list of potential fretting damage situations is, of course, even longer but can be reduced to three characteristic situations: bearings, couplings, and joints.



Sl. 1. *Lažna Brinellova poškodba na tečini valjčnega ležaja*
Fig. 1. *False brinelling damage on roller bearing race*

Preglednica 1. *Značilni stroji in naprave, kjer se freting pojavlja, ter nekatere komponente na primeru letala*
Table 1. *Specific machines and systems where fretting occurs and components damaged by fretting in an aircraft*

značilni stroji in naprave , pri katerih se pojavlja freting specific machines and systems where fretting occurs
helikopterji helicopters
letala aircrafts
vlaki trains
ladje ships
avtomobili, tovornjaki, avtobusi automobiles, trucks, buses
kmetijska mehanizacija farm machinery
ortopedski vsadki orthopaedic implants
vlečnice, dvigala z jeklenimi vrvmi wire rope systems

seznam komponent in naprav na letalu, pri katerih se običajno pojavlja freting list of components in an aircraft typically damaged by fretting
zgibni ležaj v zakrilcih aileron hinge point bearings
krmilni vezni ležaj elevator and rudder hinge point bearings
vezni ležaj lopute universal joint bearings
dvigalni zgibni ležaj flap hinge point bearings
univerzalni zgibni ležaj control pulley bearings
ležaj v motorju engine and engine control bearings
ležaj elise propeller bearings
zveze z zatiči in sorniki spline connections
objemke, spone clamps
kovice pin joints

1.1 Tečine kotalnih ležajev

Kroglični in valjčni ležaji, ki so vgrajeni zgolj za omogočanje majhnih izmeničnih premikov ali pa so v mirovanju izpostavljeni vibracijam, lahko utrpijo precejšnje fretinške poškodbe v dotikih med kotalnimi elementi in tečinami (sl. 1). Tovrstne poškodbe ležajev so lahko problem pri transportu strojev in naprav iz kraja proizvodnje na končno prodajno mesto, npr. cestni ali železniški prevoz avtomobilov.

1.2 Prilegi čepa v izvrtini

Zelo pogosto mesto pojavljanja fretinških poškodb je površina prilega pesta na gredi. Poškodba običajno nastane na robu dotika, kjer so napetosti največje (sl. 2a). Vzrok je lahko zunanja obremenitev, ki povzroči upogib gredi, kakor je shematsko prikazano na sliki 2b. V dotiku se zaradi rotacije spreminja področje natezne in tlačne napetosti, ki je najbolj izrazito prav na robu, tako da na tem mestu prihaja do največjega relativnega premika med površinama, kar privede do poškodbe. Tipičen primer je nased zobnika ali kolesa na gredi.

Drugi vzrok fretinške poškodbe v stiku čepa in izvrtine pa so vibracije, ki delujejo na mirujoča dela v stiku. V primeru kotalnega ležaja, ko se vrti notranji obroč, nastane lahko fretinška poškodba na zunanjem obroču, ki ima ohlapnejši ujem kot notranji

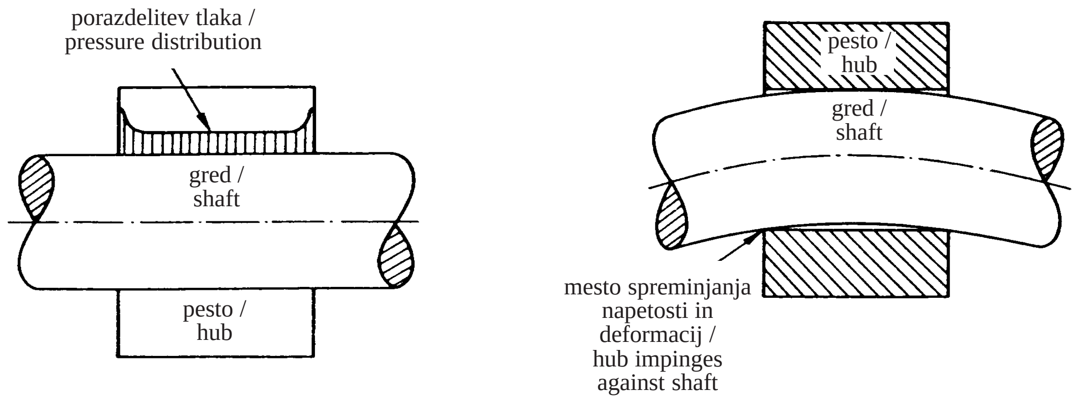
1.1 Rolling bearings races

Ball and roller bearings which are only called upon to make small oscillatory movements, or which are stationary for long periods but are subjected to vibration, can suffer severe fretting damage at the points of contact between the rolling elements and the races, as shown in Figure 1. This type of fretting, sometimes called also "false brinelling", was at one time a serious problem in automobile bearings when cars were being transported by road or rail.

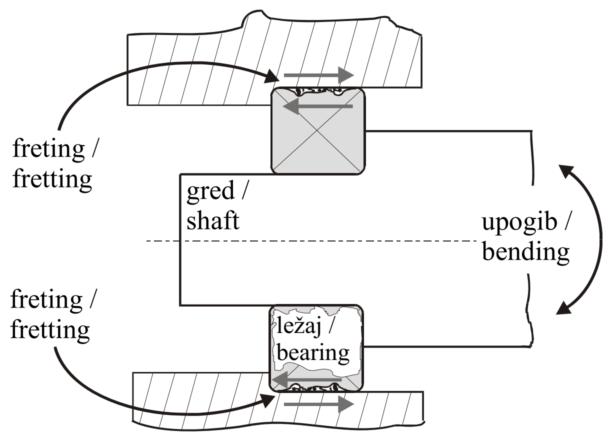
1.2 Shrink and press fits

A very common site for the occurrence of fretting corrosion is in the contact region of a member which is press - or shrink - fitted onto a loaded shaft, such as a hub on an axle. The pressure distribution under the hub rises to a maximum at the outer edges of the contact region, Figure 2(a). When the axle is loaded it is subjected to bending stresses which deform the axle, shown in Figure 2(b). As the axle rotates, each point in the surface goes through successive cycles of compressive and tensile stresses so that local movement occurs between the sleeve and the axle, the movement being greatest at the extremities of the sleeve, where the damage starts. A typical example of this kind of fretting damage is a gear on the shaft.

Another cause of fretting damage at the contact of interference fits are vibrations, acting on the stationary bodies in contact. In the case of a rolling bearing where the inner ring is rotating, a contact



Sl. 2. *(a) Porazdelitev tlaka pri tesnem nasedu, (b) vpliv obremenitve*
Fig. 2 *(a) Pressure distribution in a press fit, (b) the effect of load*



Sl. 3. *Shematski prikaz fretinške obrabe v stiku med zunanjim obročem kotalnega ležaja in okrovom, kjer prihaja do akumulacije obrabnih delcev in izgube tesnosti stika*
Fig. 3. *Schematic of the fretting wear at a contact between the rolling bearing outer race and housing, with debris accumulation and a loss of interference fit*

obroč in tako omogoča večje premike med površinama. Poškodba je na ležajih zelo pogosta in se kaže v nastajanju in akumulaciji obrabnih delcev, ki so pri železnih materialih rdečkaste barve, v končni stopnji pa vodi do izgube tesnosti prilega (sl. 3).

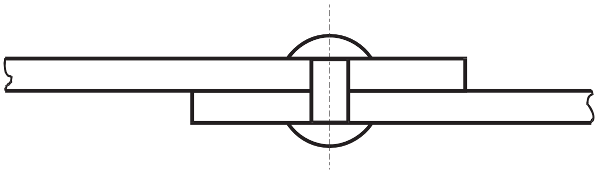
1.3 Spoji s kovicami in zatiči

Slika 4 prikazuje prerez tipičnega kovičenega spoja dveh materialov, kakršen je značilen tudi za letalska krila. Ko je tak spoj izpostavljen vibracijam ali upogibom, se lahko pojavi fretinška poškodba na več mestih: a) med glavo kovice in ploščo, b) med ploščama ter c) med stojino kovice in izvrtino. Primer s slike 5 (a), (b) jasno kaže, da poškodba na plošči pod glavo kovice ne izvira z roba izvrtine zaradi običajnega utrujanja, kakor bi bila najpogostejša prva ocena vzroka poškodbe, temveč je posledica fretinga med glavo in ploščo [6].

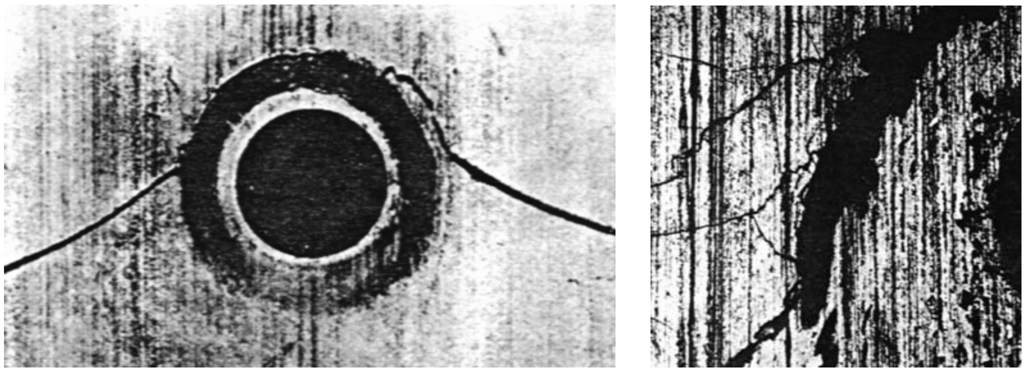
between the bearing outer ring and a housing can suffer severe fretting damage. The failure is a consequence of the formation and accumulation of wear debris, which leads to the loss of an interference fit, as presented in Figure 3.

1.3 Riveted and pin joints

Figure 4 shows a cross-section through a typical riveted joint between two sheets of material, like that frequently encountered in an aircraft structure. When a joint is vibrated or subjected to reversed, bending local movement may occur (a) between the head of the rivet and the sheet, (b) between the two sheets, and (c) between the shank of the rivet and the holes in the sheet. Figure 5 (a) shows the course of a fatigue crack emanating from the edge of the fretted region round a rivet hole. The enlarged picture (Figure 5(b)) shows clearly that the cracks don't originate at the edge of the loaded hole (classic fatigue), which could be the first impression [6].



Sl. 4. *Shematski prikaz spoja s kovico*
Fig. 4. *Schematic of the riveted lap joint*



(a) (b)

Sl. 5. *(a) Utrujenostna razpoka, ki izvira iz fretinške poškodbe pod glavo kovice , (b) detajl* [6]
Fig. 5. *(a) Fatigue crack originating from fretting damage under rivet head, (b) detail* [6]

1.4 Kirurški vsadki

Umetni ortopedski vsadki so dandanes vsakdanja stvar. Vijaki, plošče, umetni sklepi iz kovin, zlitin, keramike in polimerov nadomeščajo zdrave sklepe in pomagajo pri zdravljenju zlomljenih kosti. Večina teh vsadkov je nameščenih na okončinah telesa, ki so izpostavljene vibracijam in utrpijo precejšnje število obremenitvenih ciklov, približno 5000 dnevno [7]. Narava spojev in okoliščine torej dajejo slutiti precejšnjo možnost za nastanek fretinga. Na sliki 6 sta prikazana vijak in plošča, odstranjena po 6 mesecih s poškodovane kosti. Problem, ki se pojavlja v teh primerih, ni samo izguba tesnosti spoja, temveč tudi nastajanje obrabnih delcev, ki se sčasoma lahko naberejo v precejšnjem številu in povzročajo vnetja in poškodbe sosednjega tkiva [8]. Odzivi tkiva in uporaba primernih materialov pomeni še dandanes precejšen izziv v raziskavah [9] in [10].

2 UPORABA SODOBNIH MATERIALOV ZA GRADNJO STROJEV IN NAPRAV

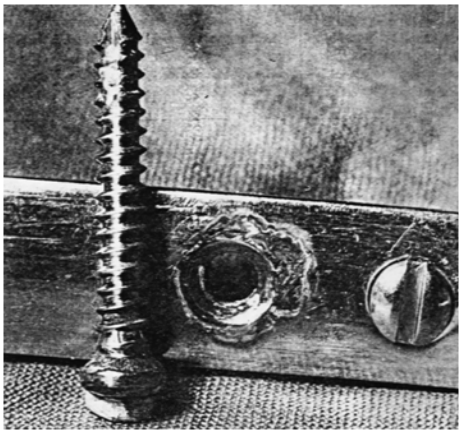
Sodobni materiali, npr.: visoko zmogljiva keramika, aluminijeve zlitine in sintrani materiali se že pogosto uporabljajo za različne strojne elemente. Njihovo uporabo zasledimo na različnih področjih, predvsem pa pri gradnji avtomobilov, letal in procesnih naprav. Razlog za nenehno večanje uporabe teh materialov je v tem, da imajo pri določenih

1.4 Surgical implants

Artificial surgical implants become more and more common in the modern world. Screws, plates, artificial joints made from metals, alloys, ceramics, and polymers help in the repair of broken bones and replace human joints. In most of the cases for broken bone applications, the metal component is attached to healthy bone by means of screws. This means that the underside of the screw and the surface of the plate are in contact. Most of these repairs are performed on limbs which can undergo a large number of stress reversals, up to about 5000 [7], in the course of one day. The conditions are therefore those in which fretting can be expected. Figure 6 shows a screw and a plate removed from a septic wound after 6 months, clearly indicating fretting damage. The problem with surgical implants is not limited only to the loosening of the contact; even more important is the generation of wear debris which can accumulate and cause damage to the living tissue [8]. Evaluating response of the human body to the use of different bio-compatible materials is still the challenge in many of today’s investigations [9] and [10].

2 USE OF ADVANCED MATERIALS IN MODERN DEVICES AND MACHINERY

Advanced materials like high performance ceramics, aluminium alloys, and various sintered materials are nowadays widely used in machine elements. They can be found in automotive, aerospace and processing devices and machinery. The outstanding properties which they provide for specific applications are the main reasons for the continuous growth



Sl. 6. *Ploščica in vijak odstranjena s kosti po šestih mesecih* [*6*]
Fig. 6. *Plate and screw removed from septic wound after six months* [*6*]

delovnih razmerah izjemno dobre lastnosti. V primeru keramičnih materialov so to predvsem protiobrabna in kemijska odpornost, zmožnost delovanja pri visokih temperaturah, velika trdota, majhna gostota itn. Čeprav je na področju obrabe dolgo vladalo prepričanje, da so ti sodobni materiali odporni proti vsem vrstam obrabnih poškodbam, tudi fretinških poškodb, se je izkazalo, da to ne drži. Vseeno pa so ostale pozitivne lastnosti in prednosti, ki jih ti sodobni materiali imajo, dovolj pomemben razlog za njihovo uporabo ter za nadaljnje raziskave na tem področju. Ker se v Centru za tribologijo in tehnično diagnostiko ukvarjamo predvsem z uporabo keramike v strojnih delih, se bomo v tem prispevku omejili na stike med keramiko in jeklom, ki je prevladujoči material v strojih in napravah.

Visoko zmogljivo keramiko lahko razdelimo v dve večji skupini [11]:

1) elektronska keramika; uporablja se zaradi dobrih električnih in magnetnih lastnosti, npr. kot izolator, grelni element, zaznavalo, podlaga, trdni elektrolit, superprevodnik itn.
2) strukturna ali konstrukcijska keramika; uporablja se zaradi dobrih a) termičnih lastnosti, kot npr. gorivne šobe, prenosnik toplote, toplotni izolator, termična ovira, ponor toplote, stator turbine itn., b) mehanskih lastnosti, kot npr. protiobrabni del, tesnilo, ležajna komponenta, rezilno orodje, motorni ventil, komponenta peči itn, c) kemijsko-bioloških lastnosti, kot npr. korozijska zaščita, nosilo katalizatorja, zaščita okolja, ortopedski vsadki (sklepi, zobje itn.).

Znotraj teh funkcijskih skupin lahko keramiko razdelimo še na monolitno keramiko, keramične prevleke in keramične kompozite. Izdelava in uporaba visoko zmogljive keramike pomeni eno od ključnih vrhunskih tehnologij, ki bodo odločale o konkurenčnosti svetovnih ekonomij v

of their use. In the case of ceramics, those properties are high wear resistance, high chemical stability, high temperature resistance, high hardness, low density etc. In the field of wear resistance it was generally accepted for many years that such high performance materials are appropriate for a wide spectra of different applications where good wear resistance is needed. However, it is now clear that this is not the case in many situations, such as in the example of fretting. Nevertheless, other excellent properties of these materials for specific applications justify their use and research activities in order to reduce the possibility of various damages. In the Centre for Tribology and Technical Diagnostics, we are active mostly in the field of research into the application of ceramics in machine elements. In this paper, various cases of contacts between ceramics and steel, the prevailing material in machine elements, are therefore presented.

Conventional ceramics present a contrast, since natural raw materials are used extensively and the broad array of properties offered by conventional ceramics remains essentially unchanged. High performance ceramics, also called advanced ceramics, can be grouped into 2 categories:

1) electronic ceramics: applications with electrical and magnetic functions i.e. insulators, heating elements, sensors, substrates, solid electrolytes, piezo-electrics, dielectrics and superconductors.
2) structural or engineering ceramics: applications including (a) thermal functions i.e. burner nozzles, heat exchangers, insulating parts, thermal barrier coatings, heat sinks, turbine vanes/stators, etc., (b) mechanical functions i.e. wear parts, seals, bearing components, cutting tools, valve train components, furnace components, etc., and (c) chemical/biological functions i.e. corrosion protection, catalyst carriers, environmental protection, and implants (joints, teeth etc.).

Within the above functional groups the materials can be further classified as monolithic ceramics, ceramic coatings and ceramic composites. High performance ceramics are one of the key emerging technologies which will determine the relative competitive positions of the world's industrial econoprihodnosti ([11] do [16]). Visoko zmogljive keramike so materiali, ki zagotavljajo znatno tehnično prednost pri delovanju sistemov, ki jih uporabljajo ([17] do [26]). Povečano uvajanje konstrukcijske visoko zmogljive keramike v strojne elemente je tesno povezano s povečanjem njihove kakovosti in zanesljivosti ([27] do [29]) ter hkrati cene [30].

V nadaljevanju se bomo osredotočili na nekaj primerov, za katere domnevamo, da se bo uporaba keramike znatno povečala, hkrati pa jim grozi možnost pojavljanja fretinških poškodb. Osnovne skupine keramike, ki se uporabljajo v teh primerih, so Si_3N_4, SiC, ZrO_2, Al_2O_3 in novejše kompozitne keramike.

mies over the next years ([11] to [16]). High performance ceramics are materials which provide significant performance benefit to the systems which utilise them ([17] to [26]). Increasing acceptance of structural ceramics into new commercial applications is closely linked with the ability to increase product quality and reliability ([27] to [29]) while simultaneously reducing cost [30].

Here, we will focus only on the structural applications which are likely to make significant gains in the near future and provide conditions under which fretting damage may occur. The principle advanced ceramic families of materials to be discussed are the Si_3N_4, SiC, ZrO_2, Al_2O_3, and the newer composite ceramics.

2.1 Visokotemperaturni prenosniki toplote

Pomembno področje uporabe sodobne keramike so prenosniki toplote. Najboljši kovinski prenosniki toplote lahko delujejo v temperaturnem območju do 1100 °C in dosegajo 20 do 30 odstotkov prihranka energije, medtem ko lahko keramični prenosniki toplote delujejo do 1400 °C in dosežejo prihranke energije do 50 odstotkov [15]. Keramični materiali, ki se za ta primer uporabljajo, so predvsem silicijev karbid in silicijev nitrid. V številnih izvedbah visoko temperaturnih prenosnikov toplote, ki uporabljajo keramične komponente, se prihranki energije dosegajo predvsem na račun delovanja pri višjih temperaturah in tlakih.

2.1 High temperature heat exchangers

An important application for modern ceramics is in the area of waste heat recovery management. The best metallic heat exchangers can operate at about 1100°C and can achieve a 20 to 30% fuel savings. Ceramics heat exchangers can operate at 1400°C and can yield fuel savings of up to 50% [15]. Materials used for industrial heat exchangers mostly include silicon carbide and silicon nitride. Fuel savings in many varieties of high temperature heat exchangers which use ceramic components are due to operation at higher temperatures and pressures than the conventional types.

2.2 Kotalni ležaji

Visoko zmogljiva keramika, še posebej silicijev nitrid, lahko znatno izboljša delovanje kotalnih ležajev. Kotalni ležaji z vroče sintranimi kotalnimi elementi iz silicijevega nitrida so pokazali bistveno izboljšanje glede trajnosti ležajev, zmožnost delovanja pri večjih hitrostih, zmanjšanja nastajanja toplote ter večjo korozijsko odpornost v primerjavi z ležaji iz jekla ([18] do [21], [27] in [31] do [36]). Želene lastnosti, ki naj bi jih keramika za uporabo v kotalnih ležajih imela, so velika lomna žilavost, velika trdota, majhen elastični modul, majhna gostota, velika upogibna trdnost, velika korozijska odpornost, visoka zgornja temperaturna meja delovanja ter postopna porušitev materiala. Razen velikega elastičnega modula silicijev nitrid zadosti vsem omenjenim kriterijem. Podobno velja za utrjen cirkonijev oksid, vendar se lušči že pri nizkih obremenitvah, zato ni primeren za to uporabo. Enako velja tudi za silicijev karbid, ki se s pridom uporablja v drsnih ležajih zaradi majhnega koeficienta trenja. Zaradi teh pomanjkljivosti se poleg silicijevega nitrida le redko uporabljajo druge vrste keramike za kotalne ležaje. Tako je postal silicijev nitrid zaradi svojih lastnosti, ki so podane v preglednici 2, najboljši material za uporabo pri kotalnih ležajih, v veliki meri pa tudi za rezilna orodja.

2.2 Rolling bearings

High performance structural ceramics, fully dense silicon nitride in particular, can significantly increase the performance of anti-friction roller and ball bearings. Hot pressed silicon nitride rolling elements have demonstrated increased fatigue life, increased speed capability, reduced heat generation, and increased corrosion resistance as compared to high performance steel bearings ([18] to [21], [27] and [31] to [36]). The desired properties for ceramics used in bearing applications are high fracture toughness, high hardness, low elastic modulus, low density, high bend strength, high corrosion resistance, high upper use of temperature and steel-like failure (small spalls). Other than its relatively high elastic modulus, fully dense silicon nitride meets or exceeds all of these criteria. Transformation-toughened zirconia also matches most of these desired characteristics and should be a good candidate for a bearing material. However, this material has a low spall stress. Silicon carbide ceramics have excellent friction and wear properties and have been used in journal bearings. However, in rolling element bearings they tend to fail catastrophically at high loads. Thus, they are rarely used as rolling element bearings. Because of the advantages of silicon nitride ceramics bearings listed in Table 2, they have already entered commercial service as machine tool and speciality bearings. Thus, silicon nitride became the leading ceramic material for rolling applications.

Preglednica 2. *Prednosti keramičnih ali hibridnih kotalnih ležajev, ki uporabljajo kotalne elemente iz* Si_3N_4
Table 2. *Performance benefits of silicon nitride ceramics bearings and ceramic hybrid bearings*

lastnost property	prednost proti jeklu benefit versus steel
trajnost zaradi obrabe wear life	do 10× večja up to 10× greater
trajnost zaradi utrujanja fatigue life	3× do 10× večja 3× to 10× greater
hitrost speed	50% večja 50% greater
temperaturno območje delovanja temperature capability	550 °C
generacija toplote heat generation	znatno zmanjšanje substantial reduction
korozijska odpornost corrosion resistance	v splošnem zagotovljena inertnost generally inert
nemagnetnost nonmagnetic	boljša natančnost pri instrumentalnih ležajih accuracy of instrument bearings
električna neprevodnost electrical insulation	preprečen ali zmanjšan električni tok preko ležaja eliminate or reduce arcing across bearings
mazanje lubrication	zmožnost mejnega mazanja marginal lubrication capability

2.3 Batni motorji in turbine

Z uporabo keramičnih komponent v batnih motorjih dosežemo učinkovitejši prihranek goriva pri plinskih turbinah in dizelskih motorjih. Keramične komponente prispevajo k prihranku goriva tudi pri bencinskih motorjih. Vloga keramičnih komponent za izboljšanje delovanja je pri različnih motorjih različna, zato so tudi zahtevane lastnosti materialov različne.

Povečane tehnične zmogljivosti in zmanjšana poraba goriva pri plinskih turbinah je povezana z lastnostjo keramike, da lahko deluje pri višjih temperaturah kot super zlitina in je hkrati ni treba hladiti. Ključni kriterij za izbor keramičnega materiala pri plinskih turbinah je torej povezan z visokotemperaturno trdnostjo, odpornostjo na toplotne sunke in trajnost.

Keramika se uporablja pri dizelskih motorjih zaradi zmožnosti delovanja pri višjih temperaturah. Keramika v zgorevalni komori zmanjša ali odpravi potrebo po vodnem hlajenju, s čimer se zmanjšajo izgube na račun trenja v njej. Keramika se lahko uporabi za izolacijo izpušnih plinov, s tem se pridobi energija iz povečane temperature izpuha. Slaba toplotna prevodnost je torej ključni kriterij za izbor vrste keramike v dizelskih motorjih.

V bencinskih motorjih lahko keramika zniža trenje na račun znižane mase ali sil vztrajnosti. Lastnosti, ki so pri tem pomembne, so obrabna odpornost, koeficient trenja, gostota in trdnost.

2.3 Reciprocating engines and turbines

The use of ceramics in heat engines can facilitate major reductions in the fuel consumption of gas turbines and diesel engines. Ceramics can also play a role in increasing the performance of vehicles with gasoline-fuelled, spark-ignited (S-I) engines. The role of ceramic components in increasing the performance of each of these engine classes is different and thus different material properties are emphasised.

Increased performance and decreased specific fuel consumption in the case of the gas turbine result directly from the ability of the ceramics to function at higher temperatures than superalloys, and to do so without cooling. The prime selection criteria for gas turbine ceramics are high-temperature strength, thermal shock resistance, and long-term durability.

Ceramics are utilised in the case of diesel engines because they can operate at elevated temperatures. Ceramics in the combustion chamber reduce or eliminate the need for water cooling. This offers the potential to eliminate the fan and the water pump, thereby reducing friction losses. Ultimately, one can use ceramics to insulate the exhaust gases and recover energy from the increased temperature exhaust. Thus, low thermal conductivity is a key selection criterion for diesel ceramics.

In the spark-ignited engine ceramics can reduce friction and reduce reciprocating mass or rotating inertia. Major selection criteria for ceramics in spark-ignited engines include wear resistance, coefficient of friction, density, and strength.

Preglednica 3. *Keramične komponente v motorjih* [*15*]
Table 3. *Ceramic components in engines* [*15*]

komponenta component	proizvajalec motorja engine manufacturer	tip motorja engine type	keramika ceramic	učinek benefit
turbinski polnilnik turbo charger	Nissan	Otto SI	sintran Si_3N_4 sintred Si_3N_4	manjša inercija lower inertia
grelni priključki glo-plugs	Isuzu	dizelski Diesel	sintran Si_3N_4 sintred Si_3N_4	hitrejši vžig faster start-up
predzgorevalna in zgorevalna komora precombustion and swirl chamber	Isuzu, Toyota, Mazda	dizelski Diesel	sintran Si_3N_4 sintred Si_3N_4	zmanjšane emisije, hitrejši vžig, manj hrupa lower emissions, faster start-up, lower noise
odmična gred rocker-arm pads	Mitsubishi	Otto SI	sintran Si_3N_4 sintred Si_3N_4	manjša obraba lower wear
povezava vbrizga goriva fuel injection link	Cummins	dieselski Diesel	sintran Si_3N_4 sintred Si_3N_4	manjša obraba, zmanjšane emisije reduced wear, reduced emissions
ventili valve	TRW-Norton/ Oldsmobile	Otto SI	Si_3N_4	manjša vztrajnost, boljše delovanje lower inertia, higher performance
držalo vzmeti ventilov valve spring retainer	Daimler Benz/ Mercedes	Otto SI	Si_3N_4	manjša teža, manj trenja lower mass, lower friction
vodilo ventilov valve guides	Daimler Benz/ Mercedes	Otto SI	Si_3N_4	manjša obraba reduced wear
konice potisne gredi push rod tips	Toshiba/ Cummins	dizelski Diesel	Si_3N_4	manjša obraba reduced wear
del vzvoda dvigalke ventilov valve lifters tappet faces	različni various	različni various	Si_3N_4, Sialon, ZrO_2	manjša obraba reduced wear
sedeži ventilov valve seats	različni various	dizelski Diesel	ZrO_2	nadzorovan tok toplote controlled heat flow

Zaradi dejstva, da se resne raziskave na področju uporabe keramičnih komponent v batnih motorjih opravljajo manj kot trideset let, je dosežen napredek izjemen. Letna proizvodnja se nenehno povečuje in pričakovati je še hitrejše zvečevanje ([11] do [16]). Preglednica 3 prikazuje nekatere keramične komponente, ki se uporabljajo v motorjih različnih proizvajalcev in prinašajo dovolj velike tehnične prednosti, da nadomestijo večjo ceno teh komponent, ([37] do [42]). Glavna prednost je predvsem zmanjšanje trenja in obrabe. S tem, ko se v sodobnejših bencinskih motorjih dodaja večje število ventilov na valj, se seveda prednost pri znižanju trenja še povečuje. Tehnične izboljšave uporabe keramike iz silicijevega nitrida za ventile so še posebej pomembne, saj se zmanjša poraba goriva za vsaj 3 odstotke, možnost povečanja hitrosti motorja pa je kar 20% [15]. Trenutno se število keramičnih

Given the fact that serious work on the application of ceramics to reciprocating engines has been underway for only about twenty years, the progress is impressive. Annual production for the components used in the reciprocating engines is growing and is expected to grow even faster ([11] to [16]). Table 3 shows some ceramic components used in different engines which provide increased performance at a level sufficiently high to compensate for their additional costs ([37] to [42]). The main advantages of these developmental components are reduction of friction and wear. As modern SI engines add more valves per cylinder the reduction of friction in the valve train takes on an increased importance. The performance benefits of silicon nitride valves are particularly impressive since the fuel economy is improved by at least 3% and an increase in engine speed by up to 20% is possible [15]. At the present time the situation regarding the number of cekomponent in proizvajalcev, ki te komponente vgrajujejo v svoje motorje, zelo povečuje.

ramic parts and the number of engine producers which use these parts is significantly increasing.

2.4 Industrijski protiobrabni deli

2.4 Industrial wear parts

Eden izmed prvih primerov uporabe visoko zmogljivih keramičnih materialov je bil za različne proti obrabne dele strojev in naprav, npr. tesnila črpalk, ustja šob za pesek, deli naprav za abrazivne mešanice, vodila za tekstilne niti idr. Zunanje in druge razmere v teh primerih so tako različne, da ni mogoče definirati materialnih lastnosti, ki bi splošno ustrezale vsem primerom. Vsekakor pa je kombinacija posebne trdote, korozijske odpornosti ter zmerna do velika trdnost vedno dobrodošla. Lastnosti, kakor so koeficient toplotne razteznosti, lomna žilavost, odpornost na toplotne sunke, gostota in drugi pa so lahko včasih pomembni, včasih pa tudi ne, odvisno od posameznega primera. To pomeni, da je treba za izbor ustreznega materiala, ki bo obrabno odporen v danih razmerah uporabe, najprej ugotoviti obrabne in torne lastnosti, kar pa se lahko doseže le s sistematičnim izvajanjem obrabnih preskusov ([43] do [55]).

Že v prejšnjih primerih je bila predstavljena izjemna pomembnost proti obrabnih lastnosti keramičnih materialov, še posebej v povezavi s komponentami v različnih motorjih in kotalnih ležajih. Poleg teh obstaja še cela vrsta primerov uporabe keramike kot proti obrabnega materiala, od papirne industrije do kirurških vsadkov in umetnih človeških sklepov. Keramika kot obrabno odporen material bo v prihodnje pomembno področje razvoja keramičnih materialov.

One of the earliest applications of high-performance structural ceramics was in wear parts for components such as sand-blast nozzles, pump seals, equipment for handling abrasive slurries, and textile thread guides. The environment and conditions to which these wear parts are subjected are so varied that it is not possible to define material properties that would be universally desired. However, the combination of high hardness, corrosion-resistance, and moderate to high strength is always desired. Properties such as coefficient of thermal expansion, fracture toughness, thermal shock resistance or density may or may not be important depending on the specific application. Consequently, for determining the best working parameters in a specific application, wear and friction behaviour must be recognised first. A broad spectrum of contact and environmental conditions, materials, and other parameters must be tested and studied for achieving this goal ([43] to [55]).

In the previous cases the importance of the wear properties of high performance ceramics have already been stressed, especially in the discussion of automotive and bearing ceramics. There are many other opportunities for the use of advanced ceramics in wear resistant applications ranging from the mining and paper industries to replacement joints for the human body. Ceramics for wear resistant applications will be an area of major growth during the forthcoming decade.

3 FRETING V STIKIH MED JEKLOM IN KERAMIKO IZ SILICIJEVEGA NITRIDA

3 FRETTING IN CONTACTS BETWEEN STEEL AND SILICON NITRIDE CERAMICS

Med keramičnimi materiali, ki se uporabljajo v primerih, kjer je možnost fretinga največja, je prav gotovo silicijev nitrid. To se nanaša predvsem na kotalne ležaje, dele batnih motorjev, npr.: ventil, sedež ventilov idn. ter različne proti obrabne dele, kakor je bilo prikazano v prejšnjem poglavju.

Poudariti je treba, da je v različnih strojnih delih najpogosteje uporabljan material še vedno jeklo. Iz tega izhaja, da povsod tam, kjer se keramična komponenta uvede v strojni del, skoraj gotovo pride do povezave med jeklom in keramiko. To je lahko znotraj zaprtega sistema, npr. med tečinami in kotalnimi elementi v hibridnem kotalnem ležaju, ali pa v različnih primerih, kot je npr. nased med ležiščem ventila in motorjem idn. Posledica tega je, da je poznavanje fretinških mehanizmov v danih kontaktih bistvenega pomena za odpravljanje in preprečevanje poškodb.

The ceramic material which is most frequently used in the components where fretting continuously threatens is silicon nitride. This refers especially to the rolling bearings, reciprocating engine parts, like valves, valve seats, valve guides, and to different industrial wear parts, as presented in the previous chapter.

It should be pointed out that today's most commonly used material in different machine parts is, however, steel. Therefore, wherever a ceramic component is introduced into the mechanical system, there exists a link - contact between steel and ceramic. This could be a contact inside a "black box" mechanical component, like in contacts of steel raceways and ceramic balls in hybrid rolling bearings or in the press fit contact between ceramic and steel, for example in a bore of the engine head where the ceramic valve guide is situated. As a consequence, the prediction and prevention of fretting wear of steel against ceramics and especially silicon nitride is of great interest.

Primerov uporabe, pri katerih prihaja do fretinga med jeklom in keramiko je še veliko več, v tem prispevku pa so bili izbrani predvsem tisti, v katerih se uporablja silicijev nitrid. Iz povedanega izhaja, da sta študij in poznavanje fretinških mehanizmov med jeklom in keramiko iz silicijevega nitrida posebej pomembna. Prav tako je jasno, da večina naprav uporablja različna maziva zaradi manjšega trenja, vendar pa nekateri izmed teh stikov včasih obratujejo brez maziva zaradi slabega režima mazanja, okvar ali zaradi samih delovnih razmer. To pomeni, da je treba poznati značilnosti obrabe v suhih in mazanih razmerah.

Čeprav so stiki silicijevega nitrida in jekla zelo pomembni in pomenijo velik potencial tudi za prihodnje, pa je raziskav na področju fretinga za te stike še vedno malo ([56] do [58]). Še več, avtorja tega prispevka nisva v literaturi zasledila nobene objave, kjer bi v takšnih stikih uporabili olje kot mazalno sredstvo. Kljub temu pa so bile v Centru za tribologijo in tehnično diagnostiko v sodelovanju še z nekaterimi ustanovami v zadnjih letih izvedene številne raziskave fretinške obrabe za stike jeklo-jeklo, keramika-keramika in jeklo-keramika. Številne razlike in posebnosti v obrabi so bile ugotovljene, o tem smo poročali v več objavah ([59] do [66]). Iz ugotovljenih razlik je treba povleči sklep, da brez poznavanja posebnosti in razlik v odzivih, tudi primernih rešitev ni mogoče podati, zato je treba še naprej za potencialne primere uporabe izvajati ustrezne raziskave, ki lahko vodijo do zmanjšanja poškodb in okvar na strojnih delih.

4 SKLEPI

- Pojav fretinških poškodb se kljub nenehnim raziskavam še vedno širi. Večina teh poškodb se zgodi na značilnih strojnih elementih, kakor so ležaji, sklopke, različni spoji in protiobrabni deli.
- Z nižanjem cene in hkratnim večanjem zanesljivosti tehnične keramike se le-ta vse pogosteje uporablja v strojnih elementih, zato je pričakovati vedno večje pojavljanje fretinga v stikih med keramiko in jeklom, ki je še vedno najpogostejši material v strojih in napravah.
- V strojnih elementih, ki so najbolj izpostavljeni možnosti fretinških poškodb in se vanje vgrajuje keramika, se uporablja silicijev nitrid. Prav zato je mehanizme fretinške obrabe med jeklom in silicijevim nitridom nujno poznati, da bi se lahko zmanjšalo nastajanje porušitev v teh stikih.

There are many more situations where the fretting wear of ceramics and steel is a problem, but only some specific machine parts were chosen because they primarily utilise steel against silicon nitride contacts. The bearing steel against silicon nitride contacts under fretting conditions are therefore a subject of special interest. From the examples of applications it is clear that some of these contacts should operate without any lubrication, or they are sometimes exposed to poor lubrication conditions due to a malfunction, on the other hand, most of the machinery uses lubricants to reduce friction and wear. Therefore, details of wear behaviour in oil-lubricated and air-dry fretting conditions are necessary to obtain.

Although silicon nitride - steel contacts are of great interest and of great potential for the future, the literature available on fretting wear for such material combinations is still very limited ([56] to [58]). Furthermore, we have not found any published paper about oil-lubricated fretting for steel - ceramics contacts. However, in the last few years, fretting studies were undertaken in the Center of Tribology and Technical Diagnostics together with cooperating institutes by investigating contacts between steel-steel, silicon nitride-silicon nitride and especially silicon nitride-steel. Differences and peculiarities in wear behaviour were revealed, about which many research papers were published. Including the work on steel-silicon nitride contacts, the list of publications can be given ([59] to [66]). From the results obtained, it should be concluded that without knowing many details of the wear behaviour reasonable conclusions and solutions for better fretting prevention are not possible. Consequently, research for particular applications must go on, hopefully leading to less fretting occurrences and damages in various devices and machinery.

4 CONCLUSIONS

- Although many research activities are taking place in the field of fretting wear, its occurrence is still increasing. Most of those occur in typical applications, like bearings, couplings, various interference fits and wear parts.
- Continuous lowering of the cost and increasing reliability of ceramics increase the use of ceramics in mechanical components. Consequently, more fretting damages in contacts between steel and ceramics are expected.
- The ceramic material which is the most frequently used in applications where fretting could occur is silicon nitride. It is therefore necessary to learn more about the fretting wear mechanisms between the steel and silicon nitride to be able to prevent a failure of machine components due to fretting.

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Naslov avtorjev: Dr. Mitjan Kalin, dipl. inž.
Prof. dr. Jože Vižintin, dipl. inž.
Center za tribologijo in tehnično diagnostiko
Fakulteta za strojništvo
Univerze v Ljubljani
Bogišičeva 8
1000 Ljubljana

Author's Address: Dr. Mitjan Kalin, Dipl.Ing.
Prof.Dr. Jože Vižintin, Dipl.Ing.
Centre for Tribology and Technical Diagnostics
Faculty of Mechanical Engineering
University of Ljubljana
Bogošičeva 8
1000 Ljubljana, Slovenia

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