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Mehanika in značilne oblike fretinga*

Mechanics and Characteristic Forms of Fretting

Mitjan Kalin - Jože Vižintin

Ena izmed oblik obrabe, ki znatno zmanjšuje trajnost strojnih delov, je tudi fretinška obraba. Freting je delovanje, ki povzroča poškodbo, ko se dve telesi, ki sta v stiku, relativno gibljeta z majhno amplitudo pomika v drsni smeri. Kljub dolgoletnemu poznavanju samega pojava, pa so podrobnosti še neraziskane. Predvsem velja to za različne pojavne oblike ter njihovo odkrivanje in odpravljanje. V prispevku so predstavljene značilnosti porazdelitve napetosti v fretinških stikih, značilne oblike površinskih poškodb ter druge značilnosti, ki ločijo freting od normalnega izmeničnega drsenja.

(Ključne besede: freting, mehanika, značilnosti, napovedi)

One of the wear forms which significantly limits the operating life of various machine components and structures is fretting wear. Fretting is the action which causes damage when two contacting bodies are subject to a relative oscillatory sliding motion of small displacement amplitude. Although the fretting phenomenon has been recognised for decades, many details about the process are still unknown. This is especially true for different fretting features, their prediction and prevention. In this paper, fretting contact mechanics, specific surface damages and other fretting particularities which distinguish fretting from normal reciprocating sliding are presented.

(Keywords: fretting, mechanics, characterization, prediction)

0 UVOD

O fretingu je prvič v zgodovini poročal Eden s soavtorji [1] leta 1911, ko je našel na jeklenih vzorcih naprave za preskušanje utrujanja rjave oksidne delce. Podrobneje je proces raziskoval Tomlinson [2], ki je v ta namen zgradil tudi preskušališče. Tako je leta 1927 definiral pojem “korozijski freting” (Fretting Corrosion), ko je opisal obliko poškodbe, ki je nastala na vzorcih po preskusu. Ta definicija fretinga in oblike fretinških poškodb se je uveljavila zaradi rdečkasto-rjavega prahu - oksida (α-Fe$_2$O$_3$), ki pogosto spremlja tovrstne poškodbe na jeklenih materialih. Kasneje so ugotovili, da se freting pojavlja tudi na materialih, ki ne oksidirajo, npr. na zlatu in platini ([3] in [4]), kar pomeni, da sam izraz ni najustreznejši. Kljub temu pa je korozijski freting ostal za dolga leta v veljavi kot izraz, ki je popisoval različne pojavne oblike fretinga.

V literaturi je dandanes najpogostejša definicija fretinga, ki pravi, da je “freting” delovanje, ki povzroča fretinško poškodbo, ko sta dve telesi, ki sta v stiku, izpostavljeni medsebojnemu relativnemu izmeničnemu gibanju z majhnimi amplitudami v drsni smeri” ([5] in [6]). Takšno gibanje se, po splošno privzeti terminologiji, imenuje tudi “zdrs”.

0 INTRODUCTION

Fretting was first reported by Eden [1] in 1911 who found that brown oxidised debris were formed in the steel grips of their fatigue machine in contact with a steel specimen. The first investigation of the fretting process, however, was conducted by Tomlinson [2] in 1927, when two machines were constructed to produce a small amplitude rotational movement between two annuli in the first case and an annulus and a flat in the second. Since the resultant debris on the steel specimens was the red iron oxide, (α-Fe$_2$O$_3$), formed as a result of a chemical reaction with oxygen in the air, he coined the phrase “fretting corrosion”. Later it was found that fretting damage can occur also on materials which do not oxidise, like gold and platinum ([3] and [4]), which contradicts the first definition. Nevertheless, the term fretting corrosion remained for many years the only definition for the different features of fretting damage.

Nowadays, the most frequently used definition of fretting is the action which causes fretting damage when two contacting bodies are subject to a relative oscillatory sliding motion of small displacement amplitude” ([5] and [6]). The required relative tangential displacement is often called “slip”.

* 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.)

Kljub temu ostaja v tej definiciji še nedorečen pojem “majhna amplituda”, oziroma kje so razlike med običajnim izmeničnim drsenjem in fretingom. Razlika je v tesni povezavi z velikostjo stične površine in njeno obliko ter temeljnimi značilnostmi fretinga. V splošnem velja, da se freting pojavlja pri amplitudah, ki so manjše od 130 µm [5], nikakor pa ne presegajo 300 µm [7]. Pri večjih zdrsih preide odziv materialov v značilen odziv za normalno drsenje. Prav majhne amplitude določajo tudi drugo glavno značilnost fretinga in to je nizka relativna hitrost med telesoma v stiku, najpogosteje okrog 1 mm/s ([5] in [8]).

Znotraj te formulacije ločimo tri osnovne oblike fretinga in s tem povezane poškodbe:

- **fretinška korozija** je oblika freting poškodbe, pri kateri so nastajajoči obrabni delci kemijski reakcijski produkti elementov tribološkega stika [9],
- **fretinška obraba** popisuje vsakršno obrabo ali poškodbo površine, ki je posledica freting procesa ([5] in [9]),
- **fretinško utrujanje** pomeni utrujanje materialov v stiku zaradi cikličnih sprememb napetosti v razmerah za freting [6].

V zadnjih letih, ko postaja razumevanje fretinškega procesa popolneješe, se vse bolj uporabljata zgolj izraza fretinško utrujanje in fretinška obraba, in sicer predvsem v povezavi s posameznimi režimi ([7], [10] do [12]) fretinga. Problem poimenovanja posameznih oblik fretinga izhaja predvsem iz pogosto težko določljive ločnice med njimi ter iz sočasnega obstoja več pojavnih oblik hkrati ([5], [13] in [14]).

Although a definition and understanding of fretting is already well established, the lack of a very stringent definition still remains in the term “small” amplitude, which does not define a transition between fretting and normal reciprocating sliding conditions. The differences are closely connected with the size of the contact area compared to the relative displacement, its shape and the basic characteristics of fretting. It is generally accepted that fretting occurs at amplitudes smaller than 130 µm [5], but not larger than 300 µm [7]. At larger amplitudes the response of materials transforms to typical sliding behaviour. Furthermore, it is the small amplitude which defines the other main characteristic of fretting, i.e. a low relative velocity between the contacting bodies, which is usually in the range of 1 mm/s ([5] and [8]).

There exist three main forms of fretting and related damage:

- **fretting corrosion** is the type of fretting damage which occurs when the resulting debris is a chemical reaction product formed from the constituents of the surface and the environment [9],
- **fretting wear** defines any type of wear or surface damage which originates from the fretting process ([5] and [9]),
- **fretting fatigue** represents fatigue of materials due to cyclic changes of the stress field under fretting conditions [6].

In recent years, as the understanding of the fretting process has improved, fretting wear and fretting fatigue are mostly used for defining the fretting damage, primarily in connection with specific fretting regimes ([7], [10] to [12]). The problem in defining certain fretting damage arises from the fact that sometimes only a tiny line of separation exists between the fatigue and wear, or both are even simultaneously present ([5], [13] and [14]).

1 MEHANIKA FRETINGA

1.1 Elastični stik

Za razumevanje mehanike fretinga je v tem prispevku podrobneje prikazan najpreprostejši elastični model ([15] in [16]), ki temelji na Hertzovi elastični teoriji [17]. Zaradi jasno definiranega napetostno-deformacijskega stanja je v modelu obravnavan stik idealno gladke krogle z ravno in idealno gladko ravno ploskvijo. V skladu s tem je po sliki 1 stična površina takih dveh teles krog z radijem a, katerega velikost je odvisna od normalne sile F_N, polmera krogle R ter elastičnega modula E in Poissonovega števila ν materiala:

1 MECHANICS OF FRETTING

1.1 Elastic contacts

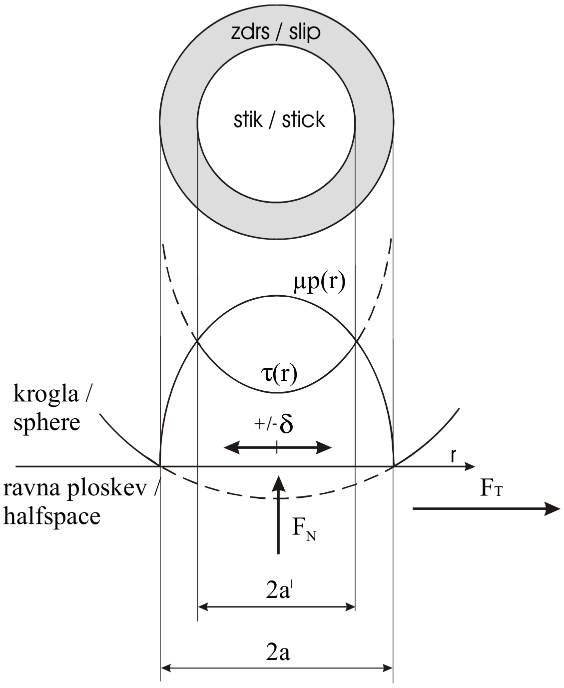
In order to explain fretting mechanics, a simple elastic model ([15] and [16]) based on Hertzian theory [17] will be used here. A stress-strain field can be very well defined at the contact of an ideally smooth ball and a flat surface. Accordingly, the contact surface of these two bodies is a circle, having a radius a, as seen from Figure 1. The value of a depends on the normal force F_N, the radius of the ball R, the elastic modulus E, and the Poisson number ν:

$$a=\sqrt[3]{\frac{3\left(1-\nu^{2}\right)F_{N}R}{2E}} \qquad (1).$$

Porazdelitev normalnega tlaka $p(r)$ po stični površini se lahko zapiše v odvisnosti od razdalje iz središča r v obliki

The distribution of normal pressure $p(r)$ over the contact area as a function of a certain radial distance r from the centre is given by:

$$\mathrm{p(r)}=\frac{3\mathrm{F_N}}{2\pi \mathrm{a}^2}\sqrt{1-\frac{\mathrm{r}^2}{\mathrm{a}^2}} \qquad (2).$$



Sl. 1. *Elastični model stika pod vplivom normalne in drsne sile*
Fig. 1. *Elastic model for surface contact under normal load and tangential force*

Če se stik obremeni hkrati še z drsno silo F_T, se pri tem vnese na površino strižno napetost $\tau(r)$, katere porazdelitev je definiral Mindlin [18] z naslednjo enačbo:

If a small cyclic tangential force F_T is superimposed on the normal load, some microslip can occur at the outer edges of the contact circle and a distribution of the shear traction $\tau(r)$, defined by Mindlin [18], can be expressed in the following form:

$$\tau(r)=\frac{F_T}{2\pi a\sqrt{a^2-r^2}} \qquad (3).$$

Iz enačbe (3) je razvidno, da ima strižna napetost singularno točko na zunanjem robu stika $(r=a)$, kar pomeni, da bi bila na tem mestu napetost neskončno velika. Ker pa strižna napetost ne more preseči napetosti, ki je na celotnem stiku definirana kot:

From the Equation (3) it is clear that the point of singularity of the tangential force is at the outer rim of the contact $(r=a)$, which means that at this point the value of the tangential force reaches infinity. Since the shear traction $\tau(r)$ cannot overcome the stress on the whole contact area, defined as:

$$\tau(r)\le \mu\, p(r) \qquad (4),$$

sledi, da pride zunaj mejnega kroga s polmerom $r=a'\le a$ do zdrsa:

it follows that at a radius larger than $r=a'\le a$, slip occurs:

$$a'=a\sqrt[3]{1-\frac{F_T}{\mu F_N}} \qquad (5).$$

To pomeni, da ima pri drsni sili $F_T<\mu F_N$, stična površina v svojem srednjem delu krog z radijem a', ki miruje in je v t.i. stičnem področju, ter zunanji del površine v obliki kolobarja, ki zdrsuje.

V področju kolobarja, ki zdrsuje $(a'\le r\le a)$, je strižna napetost podana z enačbo:

When the tangential force $F_T<\mu F_N$ is applied, a contact surface has, in its inner part, a circle of radius a' which is a stick zone. The outer part of the surface, in the form of an annulus, is a slip zone.

Surface traction distribution across the annulus in the slip zone $(a'\le r\le a)$ can be defined as:

$$\tau(r)=\frac{3\mu F_N}{2\pi a^2}\sqrt{1-\frac{r^2}{a^2}} \qquad (6),$$

v področju mirovanja - stiku ($r \leq a'$) pa z:

while within the stick zone ($r \leq a'$) by:

$$\tau(r) = \frac{3\mu F_N}{2\pi a^2}\left[\sqrt{1-\frac{r^2}{a^2}} - \frac{a'}{a}\sqrt{1-\frac{r^2}{a'^2}}\right] \qquad (7).$$

Iz izvajanja enačb (1) do (7) in slike 1 je razvidno, da se z uvajanjem drsne sile prične zdrs na zunanjem robu stične površine in se z večanjem drsne sile širi v obliki kolobarja proti središču stičnega kroga. Ko velikost drsne sile doseže pogoj $F_T = \mu F_N$, se v skladu z enačbo (5) delni zdrs v stiku spremeni v popolni zdrs prek celotne stične površine.

1.2 Elasto-plastični stik

Bolj splošen opis mehanike v fretinškem kontaktu v primerjavi z elastičnim modelom pa sta razvila Odfalk in Vingsbo [19]. V elasto-plastičnem modelu sta predpostavila, da je skupni drsni pomik sestavljen iz treh komponent, poleg elastične in zdrsne še iz pomika zaradi plastične deformacije v fretinškem stiku. Do le-te lahko pride zaradi plastične deformacije v dotikih vršičkov ter plastične deformacije samega osnovnega materiala v stiku. Tudi rezultati preskusov so potrdili, da je ta teorija dober približek dejanskemu stanju.

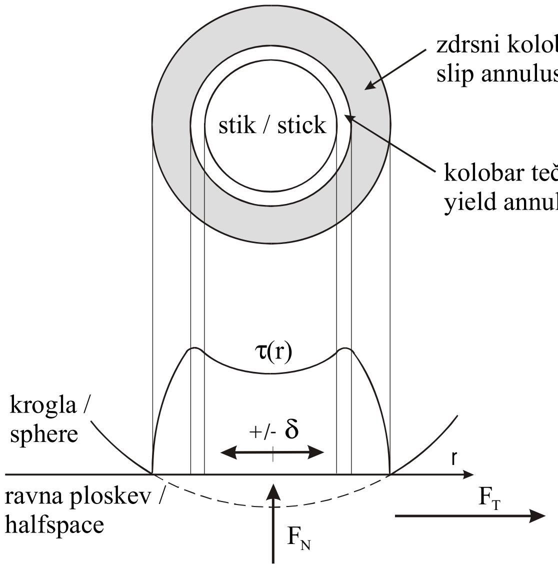
Glede elasto-plastične teorije je treba stične razmere s slike 1 nekoliko spremeniti. Področje mirovanja, v katerem se vršički deformirajo zgolj elastično, se navzven nadaljuje v kolobar, v katerem je značilna predvsem plastična deformacija vršičkov. Kolobar plastičnega tečenja je obkrožen s kolobarjem že v elastični teoriji definiranega zdrsnega področja, ki se na zunanji strani končuje z mejo stičnega področja. Shematsko je bistvo elasto-plastičnega modela prikazano na sliki 2.

From Equations (1) to (7) and Figure 1 it can be seen that in the transient phase of applying the tangential load, microslip starts at the outer rim of the contact circle and penetrates inwards as the slip annulus forms. It is shown that the inner radius of the annulus approaches zero when the applied tangential force approaches the friction force $F_T = \mu F_N$. This is the condition for incipient gross slip over the entire contact area.

1.2 Elastic-plastic contacts

A more general description of the fretting process compared to the elastic model was developed by Odfalk and Vingsbo [19] who included the contribution of plastic deformation. The consideration of elastic-plastic deformation behaviour of asperity junctions implies that the contact surface is divided into three zones, where the contact conditions are modified as shown in Figure 2. Under traction, the asperities are deformed elastically in a central stick zone, which is surrounded by a yield annulus in which the asperities have yielded plastically but have not fractured. The yield annulus, in turn, is surrounded by a slip annulus where the asperities are subjected to shear fracture in the same sense as in the elastic model.

Therefore, in the elastic-plastic model Odfalk and Vingsbo pre-supposed that the displacement is made up of three components, i.e. elastic displacement between the protrusion and the half-space (flat), plastic deformation in the bulk of the contact zone, and slip in the slip annulus. The shear traction $\tau(r)$ distribution curve in Figure 2 demonstrates the yield annulus by the rounded transition between stick and slip zones, as compared to the sharp transition for the elastic case, Figure 2.



Sl. 2. *Elasto-plastični model fretinškegs stika*
Fig. 2. *Elastic-plastic conditions in a fretting contact*

2 ZNAČILNOSTI FRETINGA

2.1 Fretinški režimi

Prav elasto-plastična teorija fretinškega stika je potrdila že prej zaznane pojave plastifikacije [7] in omogočila še stvarnejšo razlago porazdelitve področij mirovanja in zdrsa. Povezavo stičnih področij z amplitudo pomika je prvi določil Vingsbo ([7], [10] in [11]), ko je definiral različne fretinške režime. To je bil pomemben korak pri razpoznavanju fretinga, saj pomeni osnovo za definiranje stičnih razmer v odvisnosti od odziva materiala na nov način, v posebnih diagramih, izraženih kot “fretinške sheme” ([7], [10] do [12], [19] in [20]), ki so predstavljeni kasneje.

I. Režim mirovanja ($a' \approx a$)

Značilen je za najmanjše amplitude pomikov, tako da sta kolobarja tečenja in zdrsa zanemarljiva. V procesu se energija skorajda ne izgublja, tako da prikaže diagram $F_T - \delta$ premico, slika 3(a). Stične razmere določa elastična deformacija osnovnega materiala ter vršičkov v področju mirovanja prek celotnega stičnega kroga ($a' \approx a$), slika 4(a).

Poškodbe površine so minimalne in je zanje potrebno veliko število obremenitvenih ponovitev, večje od 10^6. Zaradi tega se ta režim včasih imenuje tudi “režim majhne fretinške poškodbe” [7].

II. Režim delnega zdrsa ($0<a'<a$)

Z naraščajočo amplitudo pomika dobi plastična deformacija pomembnejšo vlogo. Pojavi se tako v osnovnem materialu znotraj mirujočega področja, kakor tudi na vršičkih v obroču tečenja. Hkrati pa se v obroču zdrsa pojavi relativni zdrs med elementoma v stiku in pojavi se striženje - lom vršičkov tudi v tem področju. Diagram $F_T - \delta$, prikazan na sliki 3(b), se spremeni v histerezno zanko, katere površina pomeni izgubo energije trenja zaradi zdrsa in plastifikacije. V stiku so značilni pogoji z dvema področjema, slika 4(b).

Najbolj značilna poškodba v tem režimu je fretinško utrujanje, ki se pojavlja na meji med obema področjema. Za to področje so značilne utrujenostne poškodbe. Vplivi obrabe so minimalni.

2 CHARACTERISATION OF FRETTING

2.1 Fretting regimes

It was the elastic-plastic theory of fretting contact which confirmed the before-seen features of plastic deformation in such contacts [7] and allowed a more realistic explanation of the stick and slip zones. A connection of the contact zones with the amplitude of oscillation was determined by Vingsbo [7], [10] and [11] by defining various fretting regimes. This was an important step forward in the understanding of fretting since it provided a background for presenting the contact conditions and the response of materials in a new way, i.e. through fretting maps ([7], [10] to [12], [19] and [20]), which will be discussed later.

I. Stick regime ($a' \approx a$)

The stick regime is characteristic of the lower amplitudes of oscillation. The displacement is accommodated by elastic deformation of the asperities. The slip and yield annulus are negligible. No energy is dissipated in the process, as seen from the $F_T - \delta$ curve (line), Figure 3(a). Contact conditions are determined by the elastic deformation of the bulk material and asperities in the stick zone across the entire contact circle ($a' \approx a$), Figure 4(a).

In the stick regime, there is very limited surface damage caused by oxidation and wear, and an absence of fatigue crack formation has been observed for some studied systems up to 10^6 cycles. Consequently, wear occurring in the stick regime is sometimes called “low damage fretting” [7].

II. Partial slip regime ($0<a'<a$)

With increasing amplitude of oscillation, plastic deformation of the contact surface becomes more important. There is still a central stick region where the asperities elastically deform, and an outer annulus region where microslip occurs. Thus, plastic deformation occurs in terms of plastic yield of asperities in the yield annulus and in terms of asperities fracture in the slip zone. The $F_T - \delta$ curve, shown in Figure 3(b), changes shape from a line to a hysteresis loop. Its area corresponds to dissipated energy due to friction and plastic deformation. The contact area is characterised by two regions, as presented in Figure 4(b).

In the partial slip regime, wear and oxidation effects are small, and accelerated crack growth may result in strongly reduced fatigue life. The highest alternating stress occurs at the surface boundary between the stick and slip zones, hence it is at this point where fatigue cracks would be expected to initiate. Therefore, it is the annular microslip region where damage with characteristic fatigue cracks occurs in this fretting regime.

III. Režim popolnega zdrsa ($a' = 0$)

Ko amplituda pomika doseže kritično vrednost, da se začno pogoji za $F_T = \mu F_N$, tedaj koeficient trenja pade z največje vrednosti, kjer obstaja statični koeficient trenja, na nižjo vrednost, ki ustreza kinetičnemu koeficientu trenja. Histerezna zanka se v diagramu $F_T - \delta$ deformira, kakor prikazuje slika 3(c), saj se koeficient trenja spremeni v vsaki polovici cikla enkrat, in sicer v trenutku, ko je pomik večji od kritične vrednosti, in se pojavijo razmere popolnega zdrsa.

V skladu s sliko 4(c) je celotno področje stika izpostavljeno zdrsnim razmeram, kar se z vidika poškodb v stiku kaže z znatno obrabo. Utrujanje je zaustavljeno s prevladujočim obrabnim mehanizmom, zato se ta režim fretinga včasih imenuje tudi režim fretinške obrabe. V primeru prevladujaoče oksidacije se poimenuje tudi fretinška korozija, čeprav se zaradi sočasnega pojavljanja več tipov obrabe raje uporablja kar izraz fretinška obraba.

IV. Režim izmeničnega drsenja

Z večanjem amplitude premika prehajajo fretinške razmere s popolnim zdrsom v izmenično drsenje. Mejne razmere med obema režimoma so določene z obrabnimi mehanizmi in stopnjami obrabe, značilnimi za drsenje, ter oblikami drsne obrabe ([21] in [22]). Slika 5 prikazuje stopnje obrabe v različnih fretinških režimih za različne tipe jekel, predstavljene z obrabnim koeficientom *K* z dimenzijo ena.

V. Mešani fretinški režim

V nedavno objavljenih odkritjih [12] je predstavljen in predlagan še nov režim, imenovan mešani fretinški režim. Pojavlja se tako v področju delnega zdrsa kakor popolnega zdrsa, zato so zanj značilne poškodbe utrujanja in obrabe. Rezultati kažejo, da povzroča prav ta režim največje poškodbe v fretinških stikih. Karakterizira ga eliptična oblika histerezne zanke. Znotraj razmer mešanega režima fretinga se lahko večkrat dosežejo razmere za delni ali popolni zdrs.

2.2 Določitev fretinških režimov

Točke prehoda med posameznimi fretinškimi režimi lahko določimo s spremembami morfologije obrabne površine ali izračunanimi kriteriji, ki uporabljajo eksperimentalne podatke trenja in pomika ali zgolj teoretične modele. Prehod iz režima stika v delni zdrs ustreza odprtju fretinške histerezne zanke. V stiku se vsa vložena energija akumulira v elastično deformacijo, tako da se nič energije ne izgubi. Površina histerezne zanke je zato

III. Gross slip regime ($a' = 0$)

When the amplitude reaches a critical value, and the condition $F_T = \mu F_N$ is satisfied, the coefficient of friction (static) drops from its maximum value to a lower value, which corresponds to the kinetic coefficient of friction. A hysteresis loop represented by the $F_T - \delta$ curve in Figure 3(c) changes its shape in accordance with a coefficient of friction shift in every half cycle. This occurs at the moment when the displacement overcomes the critical value and the gross slip conditions are satisfied. The entire contact area is in the macroslip region, Figure 4(c).

In the gross slip regime, there is severe surface damage by wear, assisted by oxidation, and fretting fatigue is suppressed by the continuous elimination of the contact fatigue cracks through the wear process. This type of wear is usually termed fretting wear. As mentioned above, the term fretting corrosion can be used when oxidation takes place, but due to more general considerations and the frequent simultaneous occurrence of different surface damage features, fretting wear is now generally preferred.

IV. Reciprocating sliding regime

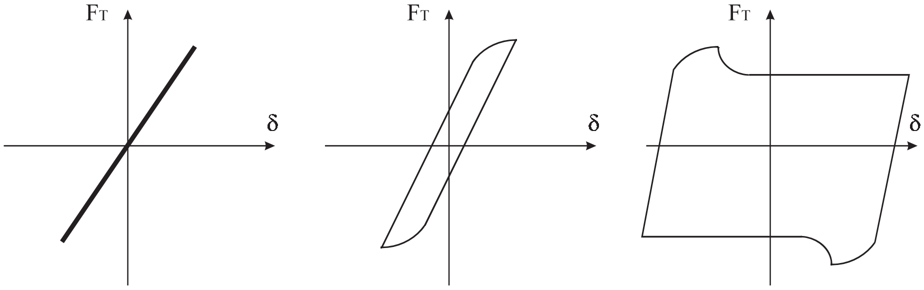
When the amplitude of oscillation is high enough, the wear mechanisms and wear rate became equal to those in reciprocating sliding ([21] and [22]). The point at which this occurs is referred to as the transition to the reciprocating sliding regime. Figure 5 shows wear rates for various fretting regimes for a wide range of steels, represented by the non-dimensional wear coefficient *K*.

V. Mixed fretting regime

Recently, a new fretting regime was suggested [12], to complement the already presented basic fretting regimes. It is named the mixed fretting regime since it occurs in partial slip and gross slip regimes, thus both fretting wear and fretting fatigue damage are observed. It was reported that this type of fretting regime could cause the highest degree of fretting damage; it is characterised by the elliptic shape of the hysteresis loop, and by the fact that partial slip and gross slip conditions can be established alternately many times.

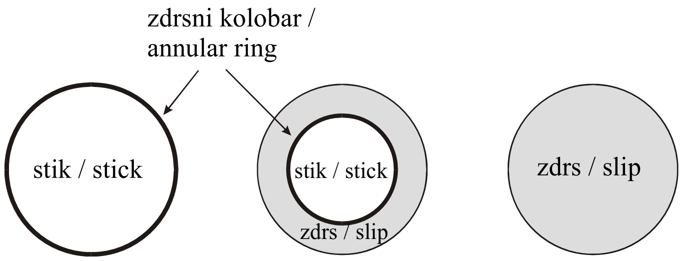
2.2 Determination of fretting regimes

The points of transition between fretting regimes can be determined by observable changes in wear scar morphology or by calculated criteria which use friction-displacement data from tests or purely theoretically obtained values. The transition from stick to partial slip regime corresponds to an opening up of the fretting hystersis loop. In the stick regime, the energy is accommodated by elastic deformation and no energy is dissipated, making the area of the loop equal to zero. Thus, a



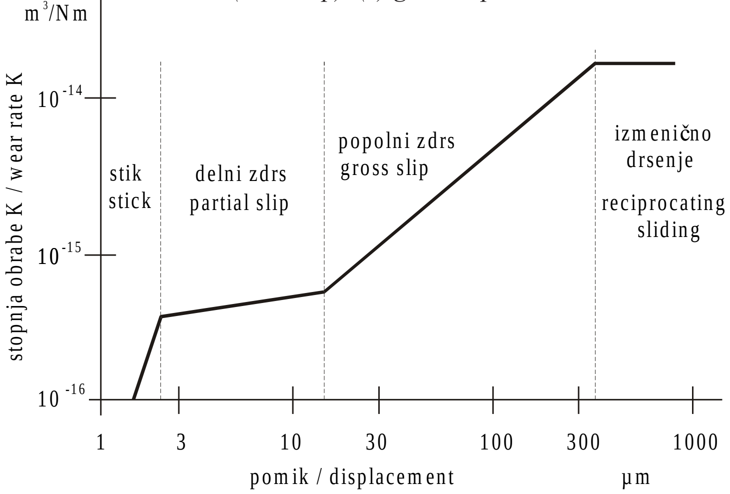
(a) (b) (c)

Sl. 3. D*iagrami* $F_T - \delta$ *za različne fretinške režime; (a) stik, (b) delni zdrs, (c) popolni zdrs*
Fig. 3. $F_T - \delta$ *plots for different fretting regimes; (a) stick, (b) partial slip, (c) gross slip*



(a) (b) (c)

Sl. 4. *Shematski prikaz stičnih razmer pri različnih fretinških režimih; (a) stik, (b) delni zdrs, (c) popolni zdrs*
Fig. 4. *A schematic of the contact conditions in different fretting regimes; (a) stick, (b) partial slip (stick-slip), (c) gross slip*



Sl. 5. *Sprememba stopnje obrabe pri različnih fretinških režimih* [7]
Fig. 5. *Variation in fretting wear rate with displacement amplitude* [7]

nič. Ko pa se z odprtjem histerezne zanke pojavi izguba energije, pomeni to prehod v režim delnega zdrsa. Prehod iz delnega v popolni zdrs pa je nekoliko težje določljiv. Na tem mestu bosta predstavljeni dve metodi, s katerima je mogoče določiti ta prehod.

V skladu z izsledki, ki sta jih predstavila Vingsbo and Schön [11], je točko prehoda v popolni zdrs mogoče določiti iz krivulje trenje - pomik ali izračunom izgube energije. Ko naraščajoči pomik δ doseže kritično vrednost popolnega zdrsa δ_{CR}, pride do padca drsne sile F_T na kritično vrednost $F_{T,CR}$, ki ustreza prehodu med statičnim in kinetičnim

value for the dissipated energy that is greater than zero corresponds to the transition from the stick regime to the partial slip regime. However, the determination of the transition from partial to gross slip is slightly more complicated, and two methods will now be discussed.

According to Vingsbo and Schön [11], the point of incipient gross slip, in terms of displacement amplitude can be found from either the friction force-displacement relations or from frictional energy dissipation. When the increasing displacement, δ, has reached the critical gross slip value, δ_{CR}, there is a drop in tangential force, F_T, to a critical value, $F_{T,CR}$ that corresponds to the transikoeficientom trenja. Ta točka (δ_{CR} , $F_{T,CR}$) torej definira kritično koordinatno točko prehoda.

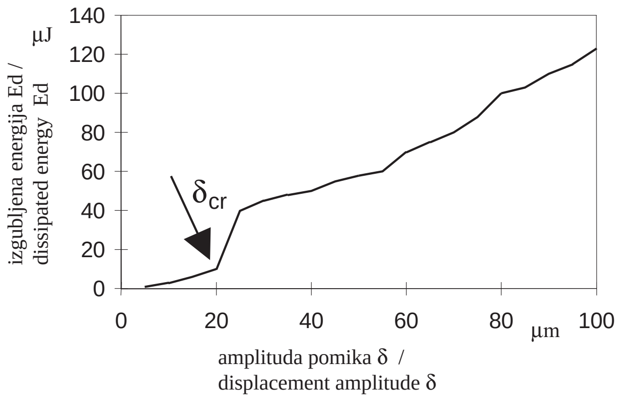
Ugotovljeno je bilo [11], da je kritično koordinatno točko prehoda lažje določiti s kriterijem izgube energije. Če prikažemo izgubljeno energijo E_d v odvisnosti od pomika δ, vedno pri določenem številu ciklov, se izkaže, da pri nekem pomiku pride do nenadnega zvečanja naklona krivulje $dE_d/d\delta$ izgube energije. Pomik, pri katerem do tega pride, imenujemo kritični pomik δ_{CR} in pomeni točko prehoda med delnim in popolnim zdrsom. Primer takega prehoda je prikazan na sliki 6.

Natančen popis analitičnih izrazov in primerjav med različnimi kriteriji je podan v literaturi [20].

tion from the static to kinetic friction. Hence, the point that coincides with the position (δ_{CR} , $F_{T,CR}$) is classified as the critical transition co-ordinate.

However, it was found [11], that the critical transition co-ordinate is easier to discern with a dissipated energy criterion. If the dissipated energy, E_d, is plotted as a function of displacement, δ, taken every time from the same certain number of cycles, it generally shows a monotonically increasing pattern. But, it was revealed that at a certain displacement, there is always a sudden increase in the slope $dE_d/d\delta$ of the energy curve for roughly the same δ as the δ_{CR} of the force curve, described above. Thus, the sudden increase in the slope of the energy curve indicates the point of incipient gross slip (Figure 6).

A detailed description in terms of analytical expressions and comparison between different criteria, including system-free, differential and theoretical mapping transition criteria is given by [20].



Sl. 6. *Diagram izgube energije v odvisnosti od amplitude pomika, ki kaže prehod med delnim in popolnim zdrsom (vrednosti so približne)*

Fig. 6. *Dissipated energy-displacement diagram showing the transition from partial to gross-slip regime (approximate values)*

2.3 Fretinške sheme

Glavni razlog, da je freting še vedno precejšnja neznanka kljub dolgoletnim raziskavam in da je eksperimentalne podatke težko primerjati, je v zapletenosti samega procesa ter številnih parametrih, ki nanj vplivajo ([8], [23] do [40]). Prav zaradi tega je tudi v praksi težko napovedati dobo trajanja fretingu izpostavljenih različnih strojnih elementov, saj je ta odvisna od specifičnih delovnih in stičnih razmer. Vingsbo [7] pa je pokazal, da je mogoče iz eksperimentalnih podatkov na podlagi dinamičnih meritev drsne sile ter amplitude pomikov razlikovati oziroma razpoznati različne fretinške režime, ki imajo pa vsak svojo značilno obliko poškodbe in mehanizem njenega nastanka. Ta ugotovitev pomeni dobro podlago za napovedovanje mogočih poškodb in dobe trajanja strojnih elementov, ki delujejo v fretinških razmerah.

Fretinška shema je diagram, ki prikazuje fretinške režime kot funkcijo dveh spremenljivk z mejami, kjer naj bi prišlo do prehoda med

2.3 Fretting maps

One of the major reasons that fretting still remains an industrial problem in spite of numerous investigations is that the experimental results are difficult to compare because of the complexity of the process itself and the many influencing parameters ([8], [23] to [40]). Because of so many contact and working conditions, it is also difficult to predict the working life of a machine component which is subjected to fretting. Vingsbo [7] showed that it is possible from the experimental data, based on dynamic measurements of tangential force and displacement, to distinguish and recognise different fretting regimes, which are characterised by different surface damage as discussed before. This is a promising finding for the prediction of possible surface damage and the working life of various machine components, working under different fretting conditions.

A fretting map is an illustration that portrays the pertinent regimes in two variables, where the regime boundaries represent the critical values posameznimi režimi [7]. Glede na številne vplivne parametre je mogoče sestaviti več fretinških shem, npr. pomik-normalna sila, pomik-frekvenca, pomik-obraba itn. Še posebej uveljavljena je shema, ki prikazuje različne režime v odvisnosti od normalne sile in amplitude pomika (sl. 7).

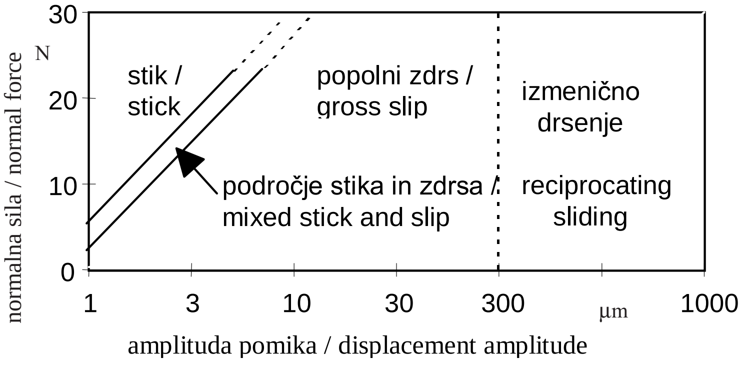
Zamisel fretinških shem je razširil Vincent [41], ki je predlagal uporabo dveh tipov fretinških shem: fretinške sheme delovnih razmer in fretinške sheme odziva materiala (sl. 8). Fretinške sheme delovnih razmer predstavljajo diagram normalne sile proti pomiku ali frekvenci gibanja. Na tej shemi je mogoče določiti tri področja, ki definirajo stik, delni zdrs in popolni zdrs. Fretinške sheme odziva materiala pa predstavljajo napetost ali ekvivalentno napetost v stiku nasproti amplitudi pomika. Področja, ki jih lahko razberemo s te sheme, so: področje brez poškodb, področje razpok in področje nastajanja obrabnih delcev - obrabno področje.

Freting sheme so torej namenjene predvsem interpretaciji eksperimentalnih rezultatov ter določanju okvirnih delovnih razmer, v katerih naj bi se ob upoštevanju določenega tribološkga sistema lahko izognili pojavu fretinga.

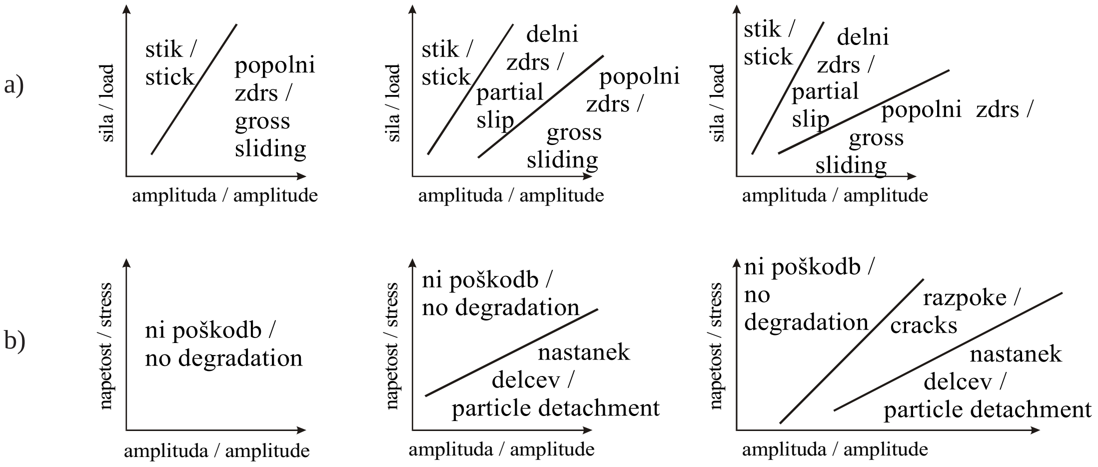
for the transition from one regime to another [7]. According to many influencing parameters, various fretting maps can be plotted, such as displacement-normal force, displacement-frequency, displacement-wear, etc. Figure 7 shows one of the most informative and widely used maps, describing fretting regimes as a function of normal load and displacement amplitude.

The concept of fretting maps has been extended by Vincent et al. [41], who suggested the use of two types of fretting maps: running condition fretting maps (RCFM) and material response fretting maps (MRFM), Figure 8. The running condition fretting maps they proposed plot the normal load versus displacement amplitude for a given frequency. The three zones identified in the RCFM are stick, partial slip and gross slip. The material response fretting map, on the other hand, plots stress or equivalent stress versus amplitude. The three zones identified in the MRFM are (1) no degradation, (2) cracks, and (3) particle detachment-wear zones.

Fretting maps are therefore used for interpretation of the experimental data and determining the boundaries for tribological and working parameters in order to get an appropriate fretting regime or even to avoid it.



Sl. 7. *Fretinška shema normalna sila - amplituda pomika* [7]
Fig. 7. *Displacement amplitude - normal force fretting map* [7]



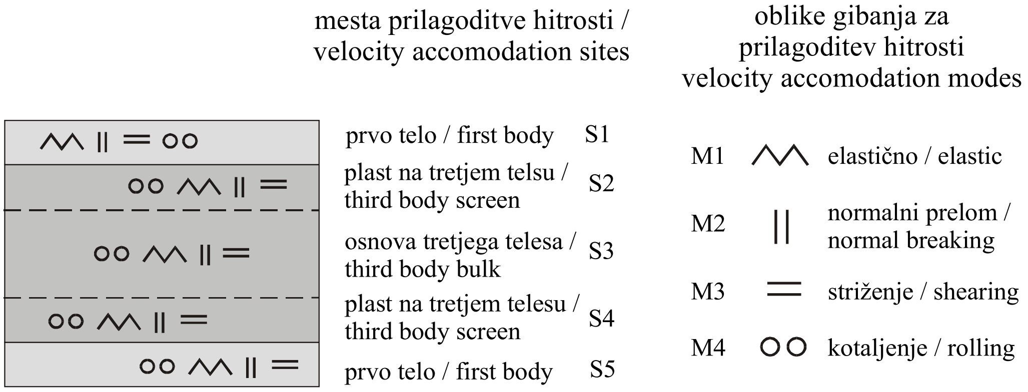
Sl. 8. *Shematski prikaz fretinških shem delovnih razmer (a) in fretinških shem odziva materialov (b) za tri različne dolžine testov (prvih deset ciklov, prvih sto ciklov, nekaj tisoč ciklov)* [41]
Fig. 8. *Schematic presentation of Running Condition Fretting Map - RCFM (a) and Material Response Fretting Map - MRFM (b) for three test durations (first ten, first hundred and first few thousand cycles)* [41]

2.4 Prilagoditev hitrosti pri fretingu

Zamisel prilagoditve hitrosti pri fretingu pomeni, da se relativni pomiki in razlika relativnih hitrosti med telesi v stiku prilagodijo na različnih mestih v stiku, v skladu z različnimi oblikami gibanja ([8], [14] in [32]). Štiri osnovne oblike gibanja (M1-M4) za prilagoditev hitrosti so elastična deformacija, lom, striženje in kotaljenje, medtem ko je mest v stiku pet (S1-S5), kakor prikazuje slika 9.

2.4 Velocity accommodation in fretting

The concept of velocity accommodation means that the relative displacement and velocity difference between the contacting bodies are accommodated at different sites and according to different modes ([8], [14] and [32]). The four basic accommodation modes (M1-M4) such as elastic deformation, fracturing, shearing and rolling and the five accommodation sites (S1-S5) in the contact are schematically indicated in Figure 9.



Sl. 9. *Mesta in oblike gibanja za prilagoditev hitrosti v stiku* [*41*]
Fig. 9. *Velocity accommodation sites and modes* [*41*]

Kombinacija omenjenih štirih oblik gibanja in petih mest v stiku omogoča 20 različnih mehanizmov prilagoditve. Spremembe v mehanizmu prilagoditve hitrosti in materialnih lastnosti pa se kažejo na razvoju koeficienta trenja.

Različni mehanizmi so na različnih mestih v stiku lahko tudi hkrati. To je npr. zelo značilno za delni zdrs. Merjena sila trenja je skupek različnih mehanizmov prilagoditve hitrosti in spreminjanja materialnih lastnosti.

2.5 Logaritermski diagrami trenja

Potem, ko so se fretinške sheme izkazale za ustrezno metodo pri razpoznavanju predvsem celotnih razmer - okvirov fretinškega procesa, se je razvoj teorije fretinga začel usmerjati v razpoznavanje fretinga znotraj posameznega režima. Izjemno uporabno orodje so logaritemski diagrami trenja [8] in [41], ki popisujejo drsno silo v odvisnosti od amplitude pomika, hkrati pa sta obe spremenljivki prikazani še v odvisnosti od števila ponovitev (sl. 10).

Logaritemski diagrami trenja razkrijejo dejanski razvoj koeficienta trenja med freting poskusom. To pa omogoča, da se koeficient trenja poveže z vplivnimi parametri pri fretingu in stičnimi razmerami v vzročno-posledično zvezo.

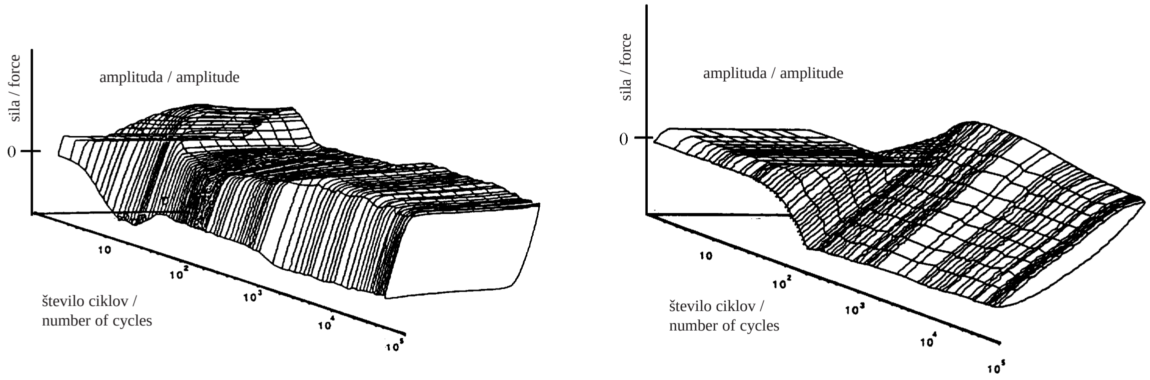
The combination of modes and sites results in 20 individual velocity accommodation mechanisms (VAM). Changes in the operative velocity accommodation mechanisms as well as in the material properties are reflected in the evolution of the macroscopically measured friction behaviour.

Different mechanisms may be operative simultaneously at different locations in the contact zone. This generally happens, for instance, in contacts subjected to partial slip conditions. The macroscopically measured tangential force thereby reflects the integral action of all velocity accommodation mechanisms operative at the fretting contact, as well as the material properties involved.

2.5 Friction logarithmic diagrams

When fretting maps confirmed their applicability as tools for recognising global fretting conditions in terms of running conditions or material response on a macroscale, a new approach was developed, i.e. friction logs [8] and [41], which helped to gain an understanding of the contact conditions on a microscale. Friction logs, sometimes called fretting logs, are three dimensional graphs that give the variation in the coefficient of friction versus displacement stroke length and time or number of cycles (Fig. 10).

Friction logs reveal the actual development of the coefficient of friction during the fretting experiment. This allow the coefficient of friction to be correlated to other influencing factors and different contact conditions.



(a) (b)

Sl. 10. *Značilni logaritemski diagrami trenja, ko so (a) opazni obrabni delci, (b) opazne razpoke* [*41*]
Fig. 10. *Representative friction log when (a) debris is formed and when (b) cracks are present* [*41*]

3 SMERI RAZVOJA PRI NAPOVEDOVANJU IN PREPREČEVANJU FRETINGA

Logaritemski diagrami trenja dejansko razkrivajo dogajanje v posameznem obremenitvenem krogu med celotnim fretinškim procesom, torej v odvisnosti od števila ponovitev. To omogoča, da se lahko spremembe koeficienta trenja povežejo z različnimi vplivnimi dejavniki ter spremembami razmer v stiku. Prav definiranje fretinga v pogledu povezovanja delovnih razmer z mogočimi poškodbami temelji na raziskavah na področju logaritemskih diagramov trenja in pomeni velik napredek zadnjih let na področju razumevanja fretinga ([42] do [46]). To pa je poleg razvoja same teorije mehanike fretinga ter vplivov na nastanek in razvoj razpok freting utrujanja ([47] do [53]) trenutno najbolj razgibana usmeritev raziskav. Vse to pa vodi k izpopolnjevanju že uveljavljenih kriterijev za nastanek in razvoj freting utrujanja ([54] do [56]) ter v končni fazi k modeliranju, napovedovanju in s tem tudi preprečevanju fretinškega utrujanja.

Poleg raziskav na področju utrujanja potekajo poglobljene raziskave tudi na področju fretinške obrabe ([57] do [60]) ter iskanju metod za natančnejšo določitev prehoda med obema vrstama poškodb ([13], [14], [20] in [61]). Vendar pa je v primeru fretinške obrabe položaj precej drugačen, saj modeliranje v pogledu analitičnega popisa mehanizmov in kriterijev nastanka poškodb ter hitrosti, velikosti in drugih njihovih lastnosti ni mogoče. Vzrok za to je predvsem v izjemni odvisnosti obrabe od številnih delovnih in stičnih razmer, saj že najmanjše spremembe, npr. samo vlažnosti zraka, povsem spremenijo mehanizem in stopnjo obrabe ([62] do [68]). Fretinška obraba je znatno odvisna od kemijskih in tribokemijskih reakcij ([69] do [78]), ki jih žal ni mogoče popisati dovolj natančno, da bi imele enačbe bistveno vrednost pri popisu procesa. Prav zato sta eksperimentalno delo in sistematičnost raziskav na tem področju toliko pomembnejši za razpoznavanje različnih vplivov in odzivov v režimu fretinške obrabe. Raziskave so torej usmerjene predvsem na določene primere uporabe, pri

3 TRENDS IN FRETTING PREDICTION AND PREVENTION

Friction logs enabled fretting conditions to be defined in a way that working conditions could be correlated to the possible forms of surface damage. This is one of the greatest improvements in understanding fretting in recent years ([42] to [46]). Investigations in this field are nowadays the most intensive field of fretting fatigue research, along with investigations on fretting mechanics in terms of effects on the fretting fatigue crack initiation and growth ([47] to [53]). Both fields have lead to the improvement of the already-established criterias for fretting fatigue damage ([54] to [56]) and to the modelling, prediction and consequently the prevention of fretting fatigue.

The other main research activities are in the fields of fretting wear ([57] to [60]) and finding better methods to distinguish the transition between fretting wear and fatigue more accurately ([13], [14], [20] and [61]). However, the situation in fretting wear research is significantly different than in fretting fatigue. Modelling, in terms of an analytical description of different mechanisms or criteria for damage initiation, growth rate and other relevant characteristics, is not possible. The reason is primarily due to the variety of influencing working parameters and contact conditions, which with only small changes can completely change the wear mechanisms and wear rates ([62] to [68]). Fretting wear is strongly dependent on chemical and tribochemical reactions ([69] to [78]), which cannot be analytically modelled accurately enough to result in equations which can give relevant results in defining the wear process. That is why systematic experimental work and research is so crucial for recognising different influences and responses in the fretting wear regime. Various investigations are therefore focused on the specific applications where fretting wear occurs; consekaterih se problemi fretinške obrabe pojavljajo. Zato so tako eksperimentalne razmere kakor materiali in druge stične razmere vnaprej določene in odvisne od danih zahtev. V tem pogledu sta tudi razpršenost raziskav v več smeri in s tem povezana nesistematičnost skoraj nujni, pa tudi razumljivi.

4 SKLEPI

- Pojav fretinga kot oblike poškodbe površin se še širi, kljub intenzivnim prizadevanjem za njegovo odpravljanje.
- Fretinška poškodba se pojavlja zaradi fretinškega utrujanja in fretinške obrabe, ki se med seboj dopolnjujeta in velikokrat delujeta tudi hkrati.
- Na področju utrujanja se odvijajo raziskave v smeri izpopolnjevanja sedanjih kriterijev za nastanek utrujenostnih razpok ter posledično modeliranju in napovedovanju utrujanja.
- Na področju fretinške obrabe se raziskave izvajajo za točno določeno uporabo z znanimi materiali ter v znanih delovnih in zunanjih razmerah.

quently, experimental parameters, materials and conditions are defined by the specific requirements of each investigation. Unfortunately, despite the mountains of data accumulated, the wide variation in experimental conditions makes the experiments mostly non-comparable.

4 CONCLUSIONS

- Fretting as a form of wear is still increasingly encountered, although a lot of research activities are going on in terms of its prediction and prevention.
- Fretting damage is a result of fretting fatigue or fretting wear, which compete with each other and many times act simultaneously.
- In the field of fretting fatigue, improvement of the already established criteria for fretting fatigue damage and finally, to modelling, prediction and consequently prevention of fretting fatigue are the main research activities.
- Fretting wear, however, is mostly studied for a specific application, with known materials, operating and environmental conditions.

5 LITERATURA
5 REFERENCES

[1] Eden E.M., Rose W.N., F.L. Cunningham (1911) Endurance of metals. *Proceedings of the Institute of Mechanical Engineers*, Vol. 4, 839-974.

[2] Tomlinson G.A. (1927) The rusting of steel surfaces in contact. *Proc. Roy. Soc. A,* Vol. 115, 472-483.

[3] Godfrey D., J.M. Bailey J.M. (1954) Early stages of fretting of copper, iron, and steel. *Lubrication Eng.,* 10, 155.

[4] Godfrey D. (1951) Investigation of fretting corrosion by microscopic observation. *N.A.C.A. Rept.*, No. 1009.

[5] Waterhouse R.B. (1972) Fretting corrosion. *Pergamon Press*, Oxford, England, 3.

[6] Waterhouse R.B. (1992) Fretting fatigue. Int. Materials Reviews, Vol.37, No 2, 77-97.

[7] Vingsbo O., S. Soderbrg (1988) On fretting maps. *Wear,* 126, 131-147.

[8] Berthier Y., Vincent L., M. Godet (1988) Velocity accomodation in fretting. *Wear,* 125, 25-38.

[9] Glossary of terms and definitions in the field of friction. (1969) *Wear, and Lubrication*, *OECD Publications*, Paris, France.

[10] Vingsbo O. (1992) Fretting and contact fatigue studied with the aid of fretting maps. In: Standardization of fretting fatigue test methods and equipment, *ASTM STP* 1159, M.H. Attia and R.B. Waterhouse, Eds., *American Society for Testing and Materials,* 49-59.

[11] Vingsbo O., J. Schön (1993) Gross slip criteria in fretting. *Wear,* 162-164, 347-356.

[12] Zhou Z.R., L. Vincent (1995) Mixed fretting regime. *Wear,* 181-183, 531-536.

[13] Bill R.C. (1983) Fretting wear and fretting fatigue - how are they related? *J. of Lubr. Technol., ASME Trans.,* Vol 105, 230-238.

[14] Berthier Y., Vincent L., M. Godet (1989) Fretting fatigue and fretting wear. *Tribology International*, Vol 22, No 4, 235-242.

[15] Johnson K.L. (1985) Contact mechanics; *Cambridge University Press*, London, New York, Sydney, p.26, 230.

[16] Hills D.A., Nowell D., A. Sackfield (1993) Mechanics of elastic contacts. *Butterworth Heinemann Ltd.*, 111, 135, 260, 367, 456.

[17] Hertz H. (1986) On the contact of rigid elastic solids and on hardeness; Miscelaneous papers. *MacMillan and Co.*, London, 163-183.

[18] Mindlin R.D. (1949) Compliance of elastic bodies in contact, *J. of Appl. Mech.*, 71, 259-268.

[19] Odfalk, M., O.Vingsbo (1992) An elastic-plastic model for fretting contact. *Wear* 157, 435-444.

[20] Fouvry S., Kapsa P., L. Vincent (1995) Analysis of sliding behaviour for fretting loadings: determination of transition criteria. *Wear,* 185 , 35-46.

[21] Nam P. Suh (1986) "Tribophysics". *Prentice-Hall*, Englewood Cliffs.

[22] Stachowiak G.W., A.W. Batchelor (1993) Engineering tribology, Tribology series, 24, *Elsevier,* Amsterdam.

[23] Dobromirski J.M. (1992) Variables of fretting process: Are there 50 of them?, In: Standardization of fretting fatigue test methods and equipment. *ASTM STP* 1159, M.H. Attia and R.B. Waterhouse, Eds., *American Society for Testing and Materials*, Philadelphia, 60-66.

[24] Soderberg S., Bryggman U., T. McCullough (1986) Frequency effects in fretting wear. *Wear,* 110, 19-34.

[25] Neymann A. (1992) The influence of oil properties on the fretting wear of mild steel. *Wear*, 152 171-181.

[26] Imai M., Teramoto H., Shimauchi Y., E. Tonegawa (1986) Effect of oil supply on fretting wear. *Wear* 110, 217-225.

[27] Bryggman U., S. Söderberg (1988) Contact conditions and surface degradation mechanisms in low amplitude fretting. *Wear,* 125, 39-52.

[28] Zhang X., C. Zhang, C. Zhu (1989) Slip amplitude effects and microstructural characteristics of surface layers in fretting wear of carbon steel. *Wear*, 134, 297-309.

[29] Bryggman U., S. Söderberg (1986) Contact conditions in fretting. *Wear* 110, 1-17.

[30] Waterhouse R.B. (1977) The role of adhesion and delamination in the fretting wear of metallic materials. *Wear*, 45, 355-364.

[31] Mohrbacher H., Celis J.P., J.R. Roos (1995) Laboratory testing of displacement and load induced fretting. *Tribol. Int.* Vol. 28, No.5, 269-278.

[32] Vincent L., Berthier Y., Dubourg M.C., M. Godet (1992) Mechanics and materials in fretting. *Wear,* 153, 135-148.

[33] Milestone W.D., J.T. Janeczko (1971) Friction between steel surfaces during fretting. *Wear*, 18, 29-40.

[34] Malkin S., D.P. Majors, T.H. Courtney (1972) Surface effects during fretting fatigue of Ti-6Al-4V. *Wear*, 22, 235-244.

[35] Greenwood, J.A., A.F. Alliston-Greiner (1992) Surface temperatures in a fretting contact. *Wear,* 155, no.2, 269-275.

[36] Zhou Z.R., L. Vincent (1993) Effect of external loading on wear maps of aluminium alloys. *Wear* 162-164, 619-623.

[37] Waterhouse R.B. (1998) The effect of surface treatment on the fatigue and fretting-fatigue of metallic materials, In Metal treatments against wear, corrosion, fretting and fatigue, Waterhouse R.B. and Niku-Lari A. (Eds), *Pergamon Press,* 31-40.

[38] Dobromirski J., I.O. Smith (1987) Metallographic aspects of surface damage, surface temperature and crack initiation in fretting fatigue. *Wear*, 117, 347-357.

[39] Husheng, Gao, Haicheng, Gu., Zhou, Huijiu (1991) Effect of slip amplitude on fretting fatigue. *Wear,* 148, 15-23.

[40] Gaul D.J., D.J. Duquette (1980) The effect of fretting and environment on fatigue crack initiation and early propagation in a quenched and tempered 4130 steel. *Metallurgical Transactions A*, Vol 11A, 1555-1561.

[41] Vincent L., Berthier Y., M. Godet (1992) Testing methods in fretting fatigue: A critical appraisal, In: Standardization of fretting fatigue test methods and equipment. *ASTM STP* 1159, M.H. Attia and R.B. Waterhouse, Eds., *Am. Soc. for Testing and Materials,* 33-48.

[42] Fouvry S., Kapsa P., L. Vincent (1996) Quantification of fretting damage. *Wear,* 200, 186-205.

[43] Fouvry S., P. Kapsa, L. Vincent, K. Dang Van (1996) Theoretical analysis of fatigue cracking under dry friction for fretting loading conditions. *Wear,* 195, 21-34.

[44] Petiot C., Vincent L., Dang Van K., Maouche N., Foulquier J., B. Journet (1995) An analysis of fretting-fatigue failure combined with numerical calculations to predict crack nucleation. *Wear* ,181-183, 101-111.

[45] Fouvry S., Ruiz F., Kapsa P., L. Vincent (1996) Stress and fatigue analysis of fretting on a stressed specimen under partial slip conditions. *Tribotest* 3-1, 23-44.

[46] Fouvry S., Kapsa P., Zahouani H., L. Vincent (1997) Wear analysis in fretting of hard coatings through a dissipated energy concept. *Wear*, 203-204, 393-403.

[47] Hills D.A., Noweell D., J.J. O'Connor (1988) On the mechanics of fretting fatigue. *Wear*, 125, 129-146.

[48] Hills D.A. (1994) Mechanics of fretting fatigue. *Wear,* 175, 107-113.

[49] Sato K. (1988) Damage formation during fretting fatigue. *Wear,* 125, 163-174.

[50] Szolwinsk P. M., T.N. Farris (1996) Mechanics of fretting fatigue crack formation. *Wear*, 198, 93-107.

[51] Nowell D., D.A.Hills (1990) Crack initiation criteria in fretting fatigue. *Wear,* 136, 329-343.

[52] Dang-Van K. (1993) Macro-micro approach in high cycle multiaxial fatigue, in D.L. Mcdowell and R-Ellis (eds.), Advances in multiaxial fatigue. ASTM STP 1191, *American Society for Testing and Materials,* Philadelphia, 120-130.

[53] Fellows L.J., D. Nowell, D.A. Hills (1995) Contact stresses in a moderately thin strip (with particular reference to fretting experiments). *Wear,* 185, 235-238.

[54] Endo K., H. Goto (1976) Initiation and propagation of fretting fatigue cracks. *Wear*, vol. 38, 311-324.

[55] Dang-Van K., Griveau B., O. Message (1982) On a new multiaxial fatigue limit criterion: theory and application, biaxial and multiaxial fatigue, in M.W. Brown and K Miller (eds.) *EGF Publication 3,* 479-496.

[56] Ruiz C., Boddington P.H.B., K.C. Chen (1984) An investigation of fatigue and fretting in a dovetail joint. *Exp. Mech.,* 24 (3), 208-217.

[57] Koenen A., Virmoux Ph., Gras R., Blouet J., Dewulf J.M., De J.M. Monicault. (1996) A machine for fretting fatigue and fretting wear testing in cryotechnical and normal environment. *Wear,* 197 , 192-196.

[58] Hoeppner D.W., V. Chandrasekaran (1994) Fretting in orthopaedic implants: a review. *Wear,* 173, 189-197.

[59] Stachowiak G.B., G.B. Stachowiak, Fretting wear and friction behaviour of engineering ceramics, Wear, 190 (1995) 212-218.

[60] Carton J.F., Vannes, A.B., L. Vincent (1995) Basis of a coating choice methodology in fretting. *Wear,* 185, 47-57.

[61] Yan P. (1993) The effect of number of cycles on the critical transition boundary between fretting fatigue and fretting wear. *Wear* 160, 279-289.

[62] Vingsbo O., Odfalk M., N.-E. Shen (1990) Fretting maps and fretting behaviour of some F.C.C. metal alloys, *Wear,* 138, 153-167.

[63] Voisin J.M., Vannes, A.B., Vincent, L., Daviot, J., B. Giraud (1995) Analysis of a tube-grid oscillatory contact: methodology for the selection of superficial treatments. *Wear*, 181-183, 826-832.

[64] McCool I.R., Waterhouse, R.B., Harris, S.J., M. Tsujikawa (1995) Lubricated fretting wear of a high-strength eutectoid steel rope wire. *Wear,* 185, 203-212.

[65] Niu X.P., Froyen, L., Delaey, L., C. Peytour (1996) Fretting wear of mechanically alloyed Al-Fe and Al-Fe-Mn alloys. *Wear,* 193, 78-90.

[66] McCool I.R., Harris, S.J., G.J. Spurr (1996) Fretting wear of a fine particulate reinforced aluminium alloy matrix composite against a medium carbon steel. *Wear,* 197, 179-191.

[67] Wu P.-Q., Mohrbacher H., J.-P. Celis (1996) The fretting behaviour of PVD TiN coatings in aqueous solutions. *Wear,* 201, 171-177.

[68] Schouterden K., Blanpain, B., Celis, J.P., O. Vingsbo (1995) Fretting of titanium nitride and diamond-like carbon coatings at high frequencies and low amplitude. *Wear,* 181-183, 86-93.

[69] Vodopivec F., Vižintin J., B. Suštarič (1996) Effect of fretting amplitude on microstructure of 1C-1.5Cr steel. *Mat. Sci and Tech.,* Vol.12, 355-360.

[70] Vižintin J., Kalin M., Novak S., Dražič G., Ives L.K., M.B. Peterson (1996) Effect of slip amplitude on the fretting wear of silicon nitride against silicon nitride. *Wear,* 192, 11-20.

[71] Kalin M., Vižintin J., S. Novak (1996) Effect of fretting conditions on the wear of silicon nitride against

bearing steel. *J. Mat. Sci Eng.* A. MSA220/1-2, 191-199.

[72] Novak S., Dražič G., Samardžija Z., Kalin M., J. Vižintin (1996) Wear of silicon nitride ceramics at fretting conditions. *J. Mat. Sci. Eng.* A, MSA215/1-2, 125-133.

[73] Kalin M., Vižintin J., S. Novak (1996) Fretting wear of silicon nitride against bearing steel contacts in lubricated and dry conditions. *Tribologia, Finnish Journal of Tribology*, Vol. 15, No. 4, 42-60.

[74] Kalin M., Vižintin J., Novak S., G. Dražič (1997) Wear mechanisms in oil-lubricated and dry fretting of silicon nitride against bearing steel contacts. *Wear*, 210/1-2, 27-38.

[75] Kalin M., J. Vižintin (1998) Use of equations for wear volume determination in fretting experiments. In press at *Wear*.

[76] Kalin M., J. Vižintin (1997) The influence of testing parameters on accuracy of equations for wear loss determination in fretting tests. *Proc. of the ISF'97*, Chengdu, P.R. China, 123-155.

[77] Novak, S., Dražič, G., Kalin, M., J. Vižintin (1999) Interactions in silicon nitride ceramics vs. steel contact under fretting conditions. *Wear*, 229/2, 1276-1283.

[78] Kalin, M. (1999) Fretting wear mechanisms in contact of steel and silicon nitride ceramics, Doctoral thesis. *Faculty of mechanical engineering*, University of Ljubljana.

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 Diagnostocs
Faculty of Mechanical Engineering
University of Ljubljana
Bogišičeva 8
1000 Ljubljana, Slovenia

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