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OŠTEĆENJA BOKOVA ZUBA ZUPČANIKA UZROKOVANA KOTRLJAJNO-KLIZNO-KONTAKTNIM ZAMOROM MATERIJALA
ROLLING-SLIDING-CONTACT FATIGUE DAMAGE OF THE GEAR TOOTH FLANKS

Robert BASAN – Marina FRANULOVIĆ – Markus LENGAUER – Božidar KRIŽAN

Sažetak: *Bokovi zuba evolventnih zupčanika izloženi su tijekom zahvata cikličkom djelovanju kontaktnih pritisaka te kombinaciji kotrljanja i klizanja. Spomenuto opterećenje može izazvati specifičnu vrstu zamora materijala koja se naziva kotrljajno-klizno-kontaktni zamor. U radu su opisane faze procesa zamaranja materijala izloženog djelovanju cikličkih opterećenja. Klasificirana su zamorna oštećenja boka zuba zupčanika te su za svaku vrstu navedeni njezini uzroci i značajke. Navedene informacije mogu poslužiti kao pomoć pri sprečavanju ili naknadnoj identifikaciji i uklanjanju problema sa zamornim oštećenjima zupčanika u prijenosnicima snage.*

Ključne riječi:
– zupčanik
– bok zuba
– zamor
– kotrljajno-klizni kontakt

Abstract: *During the meshing of involute gears, their teeth flanks are subjected to cyclic contact pressure loading and simultaneous rolling and sliding. The mentioned loading can induce a specific type of material fatigue that is commonly denoted as rolling-sliding-contact fatigue. In this work, individual phases of fatigue occurring due to the cyclic loading are described. Furthermore, different types of fatigue damage of gear teeth flanks are classified and for each type, its causes and features are given. The information presented can be used for prevention or subsequent identification and remedial action in the case of fatigue damage of gears in power transmissions.*

Keywords:
– gear
– tooth flank
– fatigue
– rolling-sliding contact

1. UVOD

Bokovi zuba zupčanika u zahvatu ciklički su izloženi izrazito visokim kontaktnim pritiscima i kombiniranom djelovanju kotrljanja i klizanja. Zbog kritičnosti tih opterećenja, oštećenja bokova zuba su, pored lomova zuba u korijenu, jedan od najčešćih načina stradavanja zupčanika pri radu [1].
Dijele se na površinski inicirana oštećenja i na ona koja su inicirana ispod površine boka zuba. Na pojavu površinski iniciranih oštećenja značajan utjecaj imaju hrapavost površine i postojeća površinska oštećenja, pa su stoga oštećenja češća kod zupčanika s grubljom površinskom obradom boka zuba koji uz to rade u problematičnim uvjetima podmazivanja. Kod visokoopterećenih ozubljenja s otvrdnutom i glatkom površinom boka zuba, za čiju se izradu primjenjuju kvalitetni materijali, češća su oštećenja koja se iniciraju ispod površine [2].

1. INTRODUCTION

During operation, gear teeth flanks are submitted to the cyclic action of exceptionally high contact pressures and the combination of rolling and sliding. Due to the nature of such loading, damage of the teeth flanks, in addition to tooth breakage at the base, is one of the most frequent causes of gear failure [1]. The resultant damage can be divided into surface initiated damage and subsurface initiated damage. Surface initiated damage is significantly influenced by surface roughness as well as existing damage and imperfections of the surface; hence, they appear more frequently on gears with a coarser flank surface finish, especially those that operate in conditions of problematic lubrication. Highly loaded gearings are usually manufactured from high quality materials and they usually feature surface-hardened and smooth teeth flanks. Subsurface damage development is typically encountered in such gearings [2].

Kod površinski otvrdnutih elemenata važno je uočiti da se od tvrde površine prema mekšoj jezgri osim tvrdoće mijenja i s njom povezana zamorna čvrstoća materijala. Zbog toga osim o intenzitetu i raspodjeli naprezanja položaj kritično opterećenih mjesta ovisi i o raspodjeli vrijednosti tvrdoće odnosno zamorne čvrstoće materijala, koje su postignute nakon njegove toplinske obrade. Nepovoljan međusobni odnos naprezanja i granice tečenja kakav se često javlja na prijelazu između tvrdoga površinskog sloja i mekše jezgre može dovesti do znatnih lokalnih plastičnih deformacija materijala. Povremena preopterećenja, koja su u pogonu neizbježna, mogu tu pojavu dodatno intenzivirati, što u pravilu dovodi do akumulacije oštećenja i u konačnici do inicijacije ispodpovršinskih pukotina. Tako nastale pukotine u velikom broju slučajeva određeno vrijeme napreduju ispod površine boka zuba, dok se ne ispune uvjeti za njihovo skretanje prema površini zuba ili u dubinu prema suprotnom boku, nakon čega dolazi do konačnog loma i otkidanja većega komada materijala pa i cijelog zuba. Utjecaji koji značajno doprinose nastanku spomenutih oštećenja bokova zuba zupčanika jesu neodgovarajuća dubina otvrdnutoga površinskog sloja, neodgovarajući profil tvrdoće po dubini otvrdnutog sloja i po visini zuba, preniska tvrdoća jezgre, povremena preopterećenja ozubljenja te nepravilnosti u zahvatu zuba izazvane netočnostima pri izradi i montaži [1 - 3]. Kako je već neizravno naznačeno, osnovni uzroci pojave spomenutih oštećenja bokova zuba, jesu ciklički promjenjiva naprezanja i deformacije materijala, odnosno njegovo zamaranje.

One of the essential features of surface hardened elements is the change of hardness from the surface to the core, which is followed by a corresponding change in the fatigue strength of the material. This is one of the reasons that positions of critical locations depend not only on stress magnitude and distribution, but also on hardness, i.e., the material hardness or fatigue strength distribution that is achieved following heat treatment. An unfavorable ratio between stress and yield stress, which is very often encountered in the transition area between a harder surface layer and a softer core, can result in significant, local plastic deformations of the material. Occasional overloads, which are inevitable during operation, can intensify this phenomenon further, which in the end results in damage accumulation and, subsurface crack initiation. Cracks initiated in this manner in a large number of cases advance below the surface for a certain period of time, until conditions are met either for their deflection towards the surface or for their deflection toward the opposite flank. This, in the end, can result in the separation and the breaking off of the larger pieces of the flank material, and in some cases, even of large sections of the tooth. Influential factors that can contribute significantly to the initiation and development of this kind of tooth flank damage are inappropriate depth of the hardened layer, improper hardness profile in the hardened layer and along the tooth height, insufficient core hardness, occasional overloads during operation, and errors in mesh due to manufacturing and assembly faults [1 - 3]. As already indirectly indicated, the principal causes of such damage occurrence are cyclic stresses and strains, i.e. material fatigue.

2. ZAMOR MATERIJALA UZROKOVAN CIKLIČKIM OPTEREĆENJEM

Pojmom zamora materijala (pri izotermnim uvjetima i temperaturama koje ne prelaze 1/3 njegova tališta) označava se proces njegova kumulativnog, progresivnog oštećivanja izazvanog periodičkim, odnosno cikličkim djelovanjem opterećenja uslijed kojih se u materijalu pojavljuju ciklička naprezanja i deformacije. Ako vrijednosti naprezanja prelaze granicu tečenja materijala u širem području, razvoj oštećenja, njegovo značajno proširenje te konačni lom nastupaju već nakon relativno niskog broja ciklusa opterećenja (približno manje od 10000). U tom slučaju riječ je o tzv. niskocikličnom zamoru materijala (engl. l*ow cycle fatigue – LCF*).

Međutim, zamor materijala i njime uzrokovan konačni lom mogu biti izazvani i cikličkim opterećenjima koja u materijalu uzrokuju nazivna naprezanja čije su vrijednosti niže od granice tečenja materijala. Plastične deformacije su tada izrazito lokalizirane i javljaju se tek u neposrednoj blizini koncentratora naprezanja. Broj ciklusa opterećenja potreban za razvoj pukotina

2. MATERIAL FATIGUE INDUCED BY CYCLIC LOADING

The term material fatigue (at isothermal conditions and at temperatures that do not exceed 1/3 of melting temperature) is used to denote the process of cumulative and progressive damaging of the material caused by cyclic stresses and strains induced by cyclic loading.

If the stresses exceed the yield stress in larger volumes of the material, damage development, its significant advancement and final failure occur after a relatively low number of loading cycles (approximately less than 10 000 cycles) and this type of fatigue is denominated as low cycle fatigue (LCF).

However, fatigue, consequent damage and final fracture, i.e. failure, can also be caused by cyclic loading where the stresses can be significantly lower than the yield stress of the material. Related plastic deformations are particularly localised and appear only in the immediate vicinity of stress raisers, i.e. stress concentrators. A number of load cycles sufficient for the development of cracks, as well as subsequent increase up to their critical size, can be quite high (more than 10 000 cycles), i njihov rast do kritične veličine u takvim okolnostima može biti i izrazito visok (veći od 10000), te se takav oblik zamora naziva visokocikličnim zamorom materijala (engl. *high cycle fatigue - HCF*). I kod jednog i kod drugog oblika zamora proces zamaranja materijala može se podijeliti u četiri faze (slika 1):

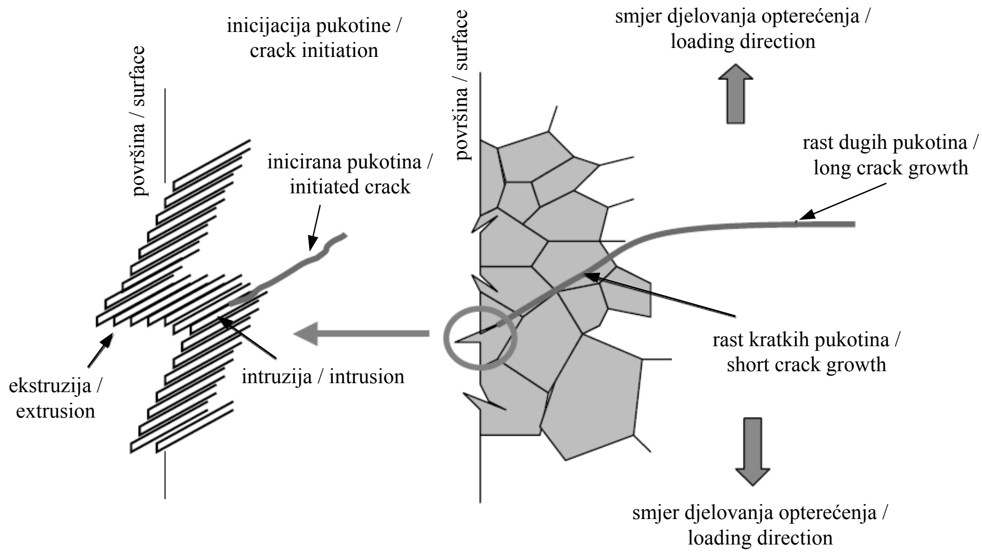
1. inicijacija pukotine
2. rast kratkih pukotina
3. rast dugih pukotina
4. lom.

pri čemu su kod niskocikličnog i visokocikličnog zamora relativni udjeli pojedinih faza u broju ciklusa opterećenja do loma, a time i njihove važnosti, bitno različiti.

hence this type of fatigue is called high cycle fatigue (HCF). Regardless of the fatigue type in question, the fatigue process can be divided into four distinct phases (Figure 1):

1. crack initiation
2. growth of short cracks
3. growth of long cracks
4. fracture.

Relative duration of individual phases and hence, their importance in considering fatigue phenomenon in case of low cycle fatigue and high cycle fatigue are quite different.



Slika 1. Faze u procesu zamora materijala s obzirom na inicijaciju i rast pukotine [4]
Figure 1. Phases in process of material fatigue regarding crack initiation and growth [4]

Inicijacija pukotine

U materijalu se uslijed opterećenja javljaju naprezanja koja u blizini koncentratora naprezanja poput uključaka, mikrošupljina, površinskih zareza i grešaka u kristalnoj strukturi mogu poprimiti vrlo visoke vrijednosti i izazvati lokalne plastične deformacije. Opetovanim djelovanjem opterećenja na takvim mjestima dolazi do cikličkog deformiranja i oštećivanja materijala, akumulacije oštećenja te u konačnici i do inicijacije pukotine [5]. Naprezanja iznad granice tečenja uzrokuju značajne plastične deformacije pa ako pukotina i ne postoji otprije, ona se u pravilu inicira već nakon nekoliko izmjena opterećenja. U slučaju povišenog intenziteta i opsega plastičnih deformacija, s njima povezana mjesta inicijacija pukotina u pravilu su mnogobrojnija i jednoliko raspodijeljena. Kod visokocikličnog zamora nazivne vrijednosti naprezanja su niske te su, osim na mjestima lokalnih koncentracija naprezanja, deformacije elastične. Zbog toga do eventualne inicijacije pukotine dolazi tek nakon vrlo velikog broja ciklusa opterećenja. Pritom se pukotine iniciraju pretežito u neposrednoj

Crack initiation

Due to the action of loading, stresses and strains develop in the material. Inclusions, microvoids, surface dents and imperfections and irregularities in the materials crystal structure can act as stress concentrators so that in their vicinity, values of stresses can reach very high values causing material to deform plastically. Repeated action of such loading causes material to deform cyclically, which in turn leads to damage and its accumulation and, ultimately to crack initiation [5]. As already mentioned, stresses above the yield stress of the material are related to more pronounced plastic deformations, so that even if a crack or a crack-like defect does not exist, it may be initiated after a couple of loading cycles. In the case of more intense and more widespread plastic deformations, crack initiation locations are usually numerous and evenly distributed across the affected zone. In the case of high cycle fatigue, nominal stresses are relatively low, so that except around stress concentrators, deformations tend to be elastic. Therefore, cracks are initiated after an number of loading cycles, and then prevalently at okolini stranih uključaka, mikrošupljina, zareza i drugih grešaka u kristalnoj strukturi, čija brojnost i raspodjela može značajno varirati od uzorka do uzorka. Budući da se pukotine pretežno iniciraju na tek nekoliko takvih, najkritičnijih mjesta, statistički rasap vrijednosti parametara zamora (mjesta i vremena do inicijacije pukotine) značajno je veći nego je to slučaj kod niskocikličnog zamora materijala [6 - 7].

Rast kratkih pukotina

Rast kratkih pukotina obuhvaća period od završetka inicijacije pukotine do njezina rasta preko nekoliko kristalnih zrna materijala. Budući da se i inicijacija i rast kratkih pukotina odvijaju na isti način, djelovanjem smičnih naprezanja odnosno smičnih deformacija, vrlo ih je teško razlikovati i razlučiti, te se nerijetko ove dvije faze promatraju zajedno i nazivaju zajedničkim imenom faza inicijacije pukotine.

Rast dugih pukotina

Ako nakon završetka inicijacije i rasta kratkih pukotina ne dođe do njihova zaustavljanja, u njihovu razvoju nastupa faza koja se naziva rast dugih pukotina. Sama pukotina, a posebice njezin vrh postaje vrlo izražen koncentrator naprezanja te u odlučujućoj mjeri utječe na raspodjelu naprezanja i deformacija u materijalu koji je okružuje. Orijentacija i smjer širenja pukotine se mijenjaju pa u ovoj fazi one napreduju okomito u odnosu na globalni smjer djelovanja glavnog normalnog naprezanja (slika 1). Budući da ova faza rasta pukotine traje sve dok pukotina ne dostigne kritičnu veličinu, nakon čega nastupa konačni lom, ona se uobičajeno naziva i fazom podkritičnog rasta pukotina [6 - 7].

Lom

Ova faza zamora materijala koja obuhvaća vrijeme propagacije pukotine od trenutka kad ona dostigne svoju kritičnu veličinu (ovisnu o materijalu, geometriji tijela, vrsti opterećenja) do konačnog loma, u većini je slučajeva iznimno kratka. Zbog toga se to vrijeme ne uzima u obzir prilikom određivanja trajnosti odnosno proračunavanja ukupnog broja ciklusa opterećenja do loma.

locations of inclusions, microvoids and imperfections in increased the material's crystal structure. The number and distribution of these elements can vary notably within the material of a single specimen as well as among different specimens. Since, cracks are initiated only at a few critical locations, statistical scatter of material fatigue parameters (crack locations, time to crack initiation) is significantly higher than is the case in low cycle fatigue [6 -7].

Growth of short cracks

The phase of short crack growth contains the period between the end of crack initiation and the beginning spread across several crystal grains. Since both—the initiation and the short crack growth phase—are governed by the same mechanism, i.e. by the action of cyclic shear strains and stresses, it is very difficult to make a clear distinction between them. They are commonly considered to be a continuous process called the crack initiation phase.

Growth of long cracks

Unless cracks cease to advance after the initiation and short crack growth phase, the so-called growth of a long crack ensues. In this case, the crack itself, and particularly its tip, becomes a very pronounced stress concentrator and starts to significantly influence stress and strain fields in its immediate proximity. Crack orientation and growth direction tend to change in order to become principally perpendicular to the global direction in which the principal normal stress acts (Figure 1). Since this phase lasts until the moment when the crack reaches its critical size, which is usually followed by sudden and final fracture, it is also known as the subcritical crack growth phase [6 - 7].

Fracture

This phase in the process of material fatigue denotes the period between the crack reaching its critical size (which is material-, geometry- and load-dependent) and the moment of final fracture. In the majority of cases, this phase is quite short and is thus, usually not taken into consideration in durability calculations, i.e. in the determination of the number of load cycles to fracture/failure.

3. ZAMORNA OŠTEĆENJA MATERIJALA BOKA ZUBA I NJIHOVA KLASIFIKACIJA

Za vrijeme trajanja zahvata bokovi zuba zupčanika međusobno se odvaljuju, pri čemu se istodobno kotrljaju i, u većoj ili manjoj mjeri, kližu jedan po drugom. Budući da se pritom s pogonskog na pogonjeni zupčanik osim gibanja prenosi i snaga, površine bokova zuba u kontaktu međusobno su pritisnute normalnim silama, a zbog trenja dodatno su opterećene i pripadnim tangencijalnim silama [8]. Zbog velike sličnosti geometrije tijela u kontaktu, uvjeta kontakta te vrste i načina djelovanja opterećenja, gotovo identična oštećenja pojavljuju se i kod valjnih ležajeva te kotača i tračnica [9 - 10].

3. FATIGUE DAMAGE OF THE TOOTH FLANK AND ITS CLASSIFICATION

During the mesh, tooth flanks of involute spur gears perform a relative motion comprised of simultaneous rolling and, to a variable degree, sliding. Since aside from movement, power is also transmitted from pinion to wheel during the mesh, surfaces of flanks in contact are mutually pressed by normal force and due to friction, they are also affected by corresponding tangential forces [8]. Due to similarity regarding the geometry of damage are encountered in rolling bearings as in rails/wheels [9 - 10]. The name by which this type of fatigue and consequent damage is identified the contacting bodies, Uobičajeni naziv za proces zamaranja materijala u takvim uvjetima te njime izazvana oštećenja je kotrljajno-klizno-kontaktni zamor materijala (engl. *rolling sliding contact fatigue - RSCF*).

U ISO normi kojom su klasificirana oštećenja zupčanika [11], oštećenja površinskog sloja materijala uzrokovana zamorom navedena su kao jedna od osnovnih kategorija. Iako do zamora i oštećivanja površinskog sloja materijala boka zuba dolazi uslijed njegova dugotrajnog cikličkog kotrljajno-kliznog opterećivanja, zbog različitosti geometrije ozubljenja, uvjeta zahvata, značajki materijala i njegove toplinske obrade, spomenuta se oštećenja mogu manifestirati na različite načine. Njihova detaljnija podjela navedena je u tablici 1.

the conditions of contact as well as type and loading action, practically identical types of is rolling-sliding-contact fatigue (RSCF).

In the ISO standard, which classifies various damage types found in gears [11], damage of the surface material layer is listed as one of the principal categories.

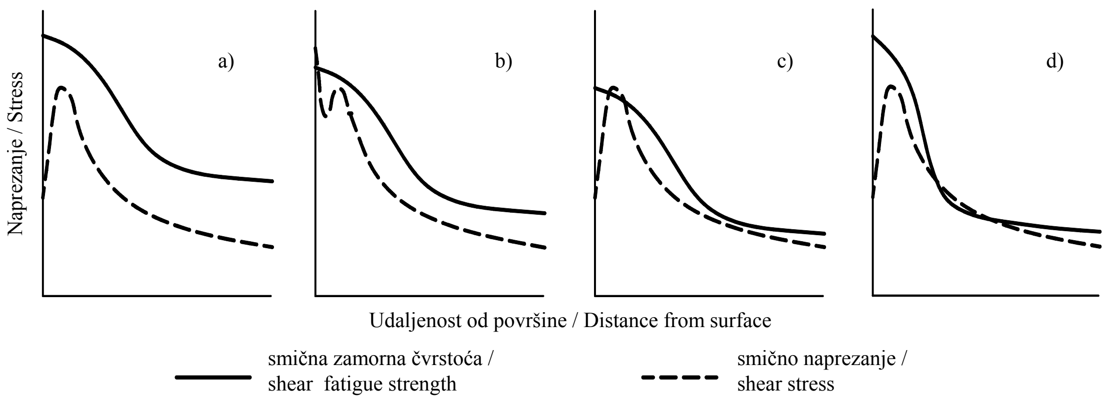
Generally, fatigue and fatigue-induced damage of the surface layer occur as a result of (usually prolonged) cyclic action of rolling-sliding contact loading. However, such damage can manifest itself in a number of different forms due to the differences in teeth geometry, meshing conditions, material characteristics and type and parameters of heat treatment. Their more detailed classification is given in Table 1.

Tablica 1. Klasifikacija zamornih oštećenja površinskog sloja materijala boka zuba prema ISO 10825
Table 1. Classification of fatigue damage of gear teeth flanks according to ISO 10825 standard

Zamorna oštećenja boka zuba zupčanika / Fatigue damage of gears tooth flank	
Jamičenje / Pitting	Inicijalno jamičenje / Initial pitting
	Progresivno jamičenje / Progressive pitting
	Mikrojamičenje / Micropitting
Flake pitting	
Spalling	
Case crushing	

Hyde [3] te Pederson i Rice [12] su kao moguće uzroke nastanka određenih vrsta oštećenja dali različite odnose profila smične zamorne čvrstoće površinski otvrdnutog materijala i raspodjele smičnog naprezanja izazvanog kotrljajno-klizno-kontaktnim opterećenjem (slika 2). Mjesta na kojima smično naprezanje prelazi smičnu zamornu čvrstoću materijala vjerojatna su mjesta nastanka zamornih oštećenja.

Hyde [3] and Pederson and Rice [12] have given simplified relations between the shear fatigue strength profiles of surface-hardened materials and the distribution of shear stresses caused by rolling-sliding-contact loading as possible causes of fatigue damage (Figure 2). Locations at which the shear stresses exceed the shear fatigue strength are the most likely sites for damage initiation.

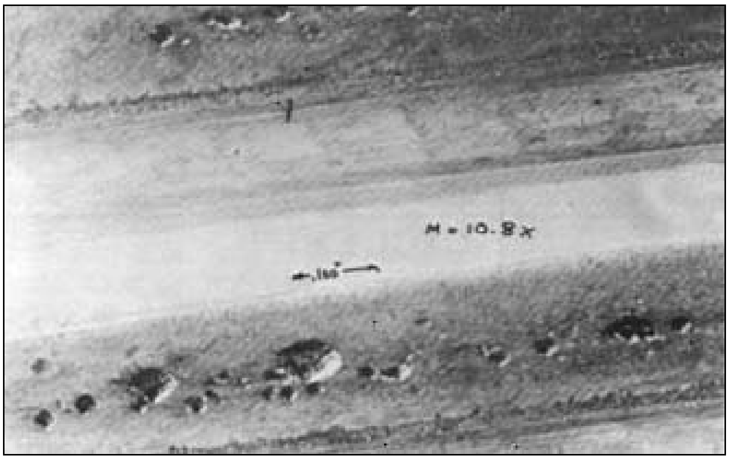


Slika 2. Mogući odnosi smične zamorne čvrstoće i smičnog naprezanja i najvjerojatnije mjesto i oblik oštećenja: a) bez oštećenja, b) površinsko oštećenje (jamičenje), c) oštećenje neposredno ispod površine (flake pitting, spalling), d) oštećenje duboko ispod površine (case crushing) (prema [3]*)*

Figure 2. Possible relations between shear fatigue strength and shear stress and the most likely location and form of damage: a) no damage, b) surface damage (pitting), c) damage immediately below surface (flake pitting, spalling), d) damage in deep subsurface layers (case crushing) (according to [3]*)*

Jamičenje (engl. *pitting*) je općeniti naziv za oštećenje površine bokova zuba u vidu pukotina odnosno jamica, čiji promjer može iznositi od nekoliko desetinki milimetra do nekoliko milimetara, a u slučaju velikih ozubljenja i više (slika 3). Neovisno o vrsti, jamičenju su izloženiji zubi pogonskog zupčanika zbog češćeg ulaženja u zahvat i to posebice njihovi dijelovi oko i ispod kinematskog kruga zbog ukupno nepovoljnije kombinacije visine i načina djelovanja opterećenja na tom dijelu bokova zuba.

Pitting is a general term that denotes crack-like damage of gear teeth flanks in the form of small pits whose diameter can range from a couple of tenths of a millimeter in smaller gears, up to several millimeters in gears with large modules (Figure 3). Regardless of gearing type, pinion teeth are more susceptible to this type of damage as they enter the mesh more often than the teeth of the wheel. Part of the tooth flank immediately below the pitch line is particularly at risk due to an adverse combination of loading magnitude and rolling/sliding conditions.



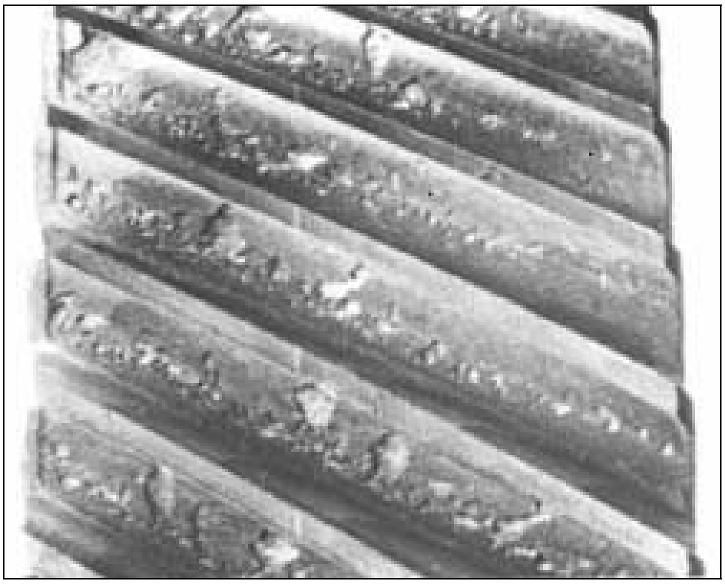
Slika 3. Jamičenje na bokovima zuba [13]
Figure 3. Pitting on gears teeth flanks [13]

Inicijalno jamičenje javlja se samo u početnim fazama rada zupčastog para i to na mjestima koja su zbog lokalnih geometrijskih nepravilnosti i hrapavosti površine boka izložena većim kontaktnim pritiscima i izravnom metalnom kontaktu. Nakon zaglađivanja površine bokova zuba u kontaktu opterećenje se raspodjeljuje na veću površinu, a naprezanja u površinskom sloju materijala smanje se ispod razine kod koje dolazi do oštećivanja, te se jamičenje zaustavlja.
Progresivno jamičenje uzrokovano je zamorom materijala i inicijacijom mikropukotina na površini ili ispod nje. Rastom i eventualnim spajanjem pukotina te njihovim izbijanjem na površinu dolazi do odvajanja i otkidanja manjih ili većih komadića materijala nakon čega na tim mjestima ostaju jamice različitih promjera i dubina (slika 4). Kao najčešća mjesta nastanka površinski iniciranog jamičenja navode se mikroneravnine uzrokovane strojnom obradom bokova (glodanje, brušenje), greške i/ili strani uključci u materijalu te toplinskom obradom uzrokovani poremećaji u strukturi materijala. U slučaju ispodpovršinski iniciranog jamičenja, pukotine pretežno nastaju u području u kojem smično naprezanje uzrokovano kotrljajno-kliznim opterećenjem dostiže svoje najveće vrijednosti. Budući da progresivno jamičenje ne uzrokuju samo lokalne nepravilnosti i hrapavost bokova zuba, ono napreduje i

Initial pitting usually appears in the first phases of gear pair operation, i.e. running in, and primarily areas that are subjected to increased surface pressures and even limited metal-to-metal contact due to the local geometrical irregularities and surface roughness. After initial smoothing of mating flank surfaces, loading is distributed across a wider area of tooth flank. This effectively lowers surface pressures and stresses in surface layers below the critical level and prevents further formation of pits.
Progressive pitting is primarily caused by fatigue of the surface material and by initiation of microcracks at and below the surface. Growth and coalescence of individual cracks and their reaching of the surface causes separation and breaking off of smaller and larger pieces of the material, leaving dents and pits in the flank's surface (Figure 4). The locations on which such cracks are most likely to initiate are surface irregularities and machining marks (milling, grinding), material defects and inclusions and distortions in the material structure caused by heat treatment. In the case of subsurface initiated pitting, cracks appear predominantly in an area in which shear stresses caused by rolling-sliding loads reach their highest values. Since progressive pitting is not caused primarily by local defects and tooth flank surface roughness, it continues to grow and advance even after initial running-in processes and the smoothing-out of the

nakon završetka početnog zaglađivanja površina bokova Kontinuiranim širenjem jamičenja smanjuje se nosiva površina bokova zuba. U izraženijim slučajevima može doći do gubitka izvornog profila zuba, a time i do prekomjernih vibracija te porasta dinamičkih opterećenja koja mogu uzrokovati i konačni lomi zuba odnosno stradavanje zupčanika.

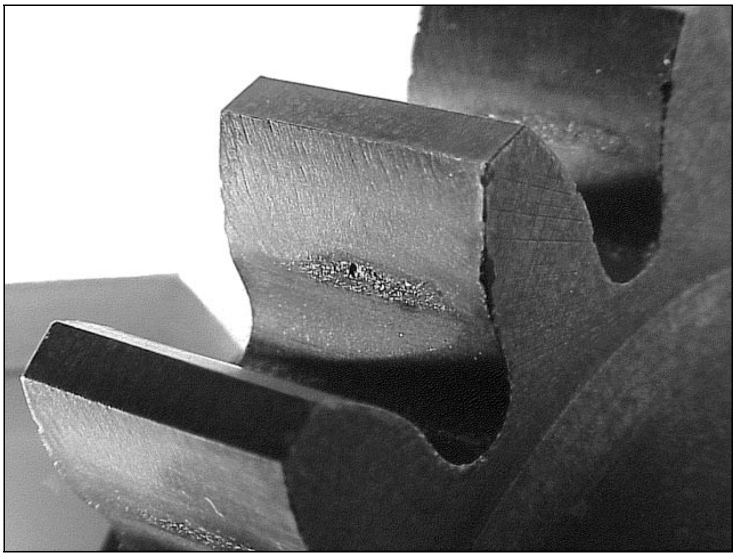
contacting surfaces is finished. Pittings progress further reduces the effective load carrying area of the flank. In more extreme cases, this can lead to the serious deterioration of the original flank profile and to excessive vibrations and dynamic loads during the mesh, which can even cause tooth fracture and gear failure.



Slika 4. Progresivno jamičenje na bokovima zuba [13]
Figure 4. Progressive pitting on gears teeth flanks [13]

Mikrojamičenje označava pojavu velikog broja plitkih mikropukotina i jamica dubine do nekoliko mikrona zbog kojih zahvaćeni dijelovi površina boka zuba poprimaju „smrznuti“ ili mat-sivi izgled (slika 5).

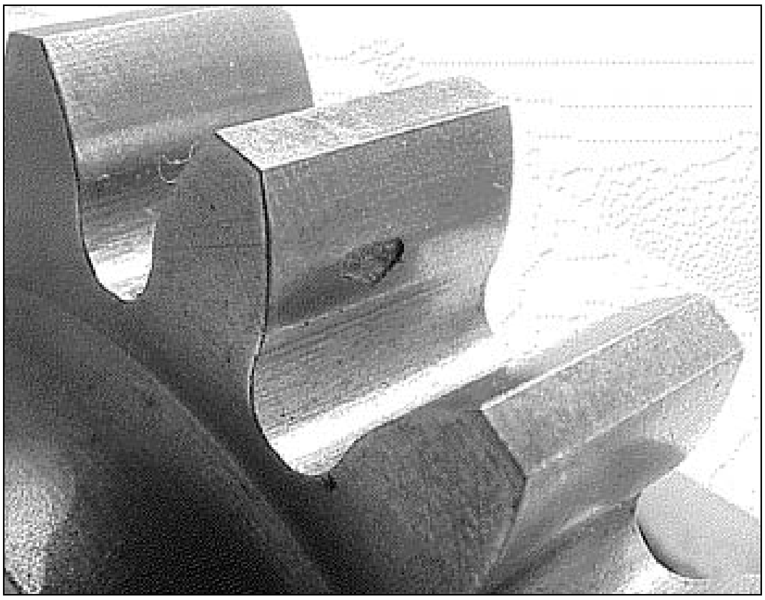
Micropitting denotes the appearance of a large number of shallow microcracks and small pits with depths on the order of several microns that cause the affected surface to appear “frozen” (Figure 5).



Slika 5. Mikrojamičenje [14]
Figure 5. Micropitting [14]

Uslijed izravnog kontakta, vrhovi neravnina se dijelom plastično deformiraju, a dijelom otkidaju, što vrlo brzo dovodi do oštećenja plitkog površinskog sloja materijala zuba i stvaranja spomenutih mikropukotina.
Cijeli proces može biti dodatno potpomognut i intenziviran manjkavim uvjetima podmazivanja jer toplina stvorena tijekom zahvata dodatno smanjuje viskoznost ulja i stanjuje uljni film. To može dovesti do njegova probijanja i izraženijeg metalnog kontakta na širem području pa i na cijeloj površini bokova zuba. Iako ovaj oblik oštećenja površine sam po sebi nije izrazito kritičan te u slučaju dobrog podmazivanja može doći do njegova zaustavljanja, postoji mogućnost da u određenim uvjetima daljnje širenje na taj način iniciranih mikropukotina dovede do ozbiljnijeg oštećenja površine.
Engleskim pojmom **flake pitting** (engl. *flake* = pahuljica, tanki list) označava se oštećenje trostranog oblika na širem području boka zuba kako je prikazano na slici 6. Nastaje odvajanjem tankih ljuskica materijala od osnovnog materijala zuba.

Direct contact causes the tips of surface microirregularities to be partly deformed plastically and to be partially sheared off, which promptly leads to damage in the shallow surface layer that results in the mentioned microcracks. The whole process can be further intensified if lubrication conditions are not adequate because direct metal to metal contact generates additional heat, which further reduces oil viscosity and thinning of the oil film. This can eventually lead to the breakdown of the oil film and an increase in the direct contact between flanks across the wider area. This form of damage by itself is not particularly detrimental, and in the case of good lubrication, it usually does not progress further. However, under certain conditions it can spread further and cause more pronounced and critical damage of the gear tooth flank.
By the term **flake pitting**, characteristic, triangle-shaped damage of a larger area of the tooth flank is denoted. Relatively thin pieces of flank material peel off of the tooth base material, leaving a characteristic shallow pit behind, as shown in Figure 6.

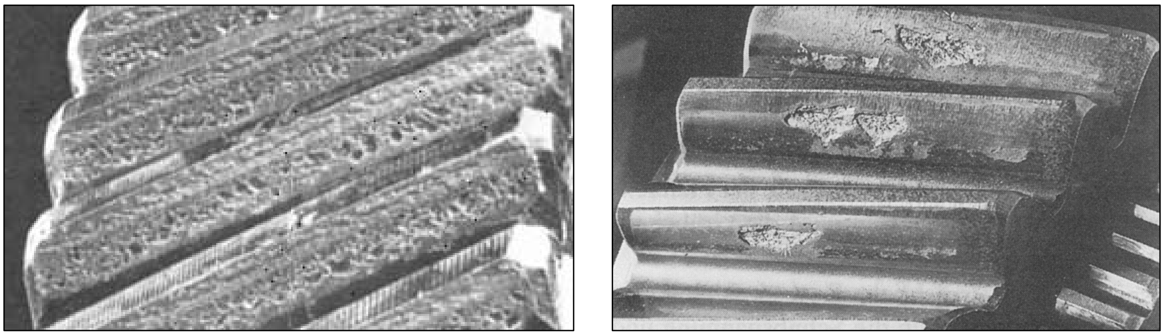


Slika 6. *Flake pitting* [14]
Figure 6. *Flake pitting* [14]

Engleski pojam **spalling** (engl. *spall* = krhotina) naziv je za ispodpovršinski inicirano oštećenje slično tzv. *flake pittingu* koje se također u pravilu prostire preko većih dijelova površine boka zuba, ali kod kojeg su ljuske veće debljine (slika 7). Inicirane pukotine se u početku šire ispod površine zuba i to paralelno s njom, da bi nakon dostizanja određene veličine skrenule prema površini zuba. Kod zupčanika s površinski otvrdnutim zubima nakon toga dolazi do odvajanja većeg komada površinskog sloja zuba, pri čemu na boku ostaje značajno oštećenje u obliku plitke jame čije se dno u pravilu nalazi na prijelazu između tvrdog površinskog sloja materijala i

Spalling is the name for subsurface initiated fatigue damage, which is rather similar to the already mentioned flake pitting. It also usually stretches over larger portions of the tooth flank, but with spalls being generally of greater thickness (Figure 7). Initiated cracks grow and advance parallel to the surface and after reaching a critical size, deviate toward the flank's surface. At gears with surface hardened teeth flanks, very often larger pieces of the material fall off, leaving significant damage in the form of a shallow pit. The bottom of the pit is usually located at the transition layer between the harder surface material and the softer core. When this type of mekše jezgre. Kod prokaljenih ili neotvrdnutih zupčanika riječ je o masovnim nakupinama povezanih i međusobno preklapajućih plitkih jamica sličnih onima kod jamičenja, ali većih izmjera.

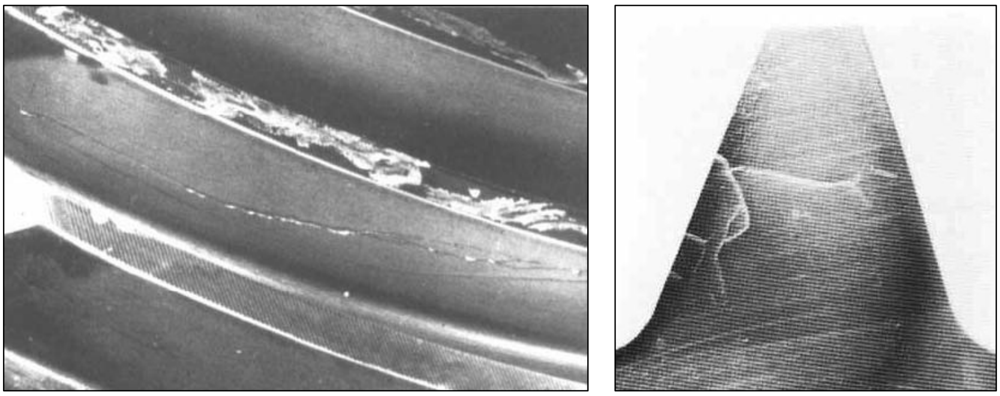
damage occurs on through-hardened or non-hardened gears, in more advanced stages it typically manifests itself in the form of a large number of shallow, overlapping pits, similar to those encountered in pitting, but of greater dimensions.



Slika 7. *Spalling* [13], [15]
Figure 7. *Spalling* [13], [15]

Engleskim nazivom **case crushing** označava se specifično oštećenje uzrokovano značajnim preopterećenjima, koje se pojavljuje uglavnom na zubima s cementiranim bokovima. Ispod otvrdnutog površinskog sloja materijal se u značajnoj mjeri plastično deformira, što dovodi do inicijacije zamornih pukotina. Opetovano djelovanje opterećenja potiče njihovo širenje paralelno s površinom boka te nakon određenog vremena skretanje prema jezgri i/ili prema površini zuba (slika 8). Zbog svega navedenog, u zahvaćenom dijelu, jezgra prestaje pružati adekvatan oslonac površinskom sloju te se on u velikim komadima odvaja od osnovnog materijala zuba.

The term **case crushing** indicates a specific type of damage, which is most often the consequence of excessive overloads and appears primarily in the case of hardened teeth flanks. Below the case-hardened surface layer, material deforms plastically, which leads quite rapidly to the initiation of fatigue cracks. Repeated subsequent (over)loads cause these subsurface cracks to initially advance parallel to the surface and after awhile to deviate toward the core and/or toward the surface (Figure 8). Due to this, in the affected area, the softer core no longer gives support to the surface layer, which starts to break off in the form of rather large pieces of material.



Slika 8. *Case crushing* [13]
Figure 8. *Case crushing* [13]

4. ZAKLJUČAK

Zahvat evolventnih zupčanika putem kojeg dolazi do prijenosa gibanja i snage s jednog zupčanika na drugi, vrlo je složen. Na značajke i vrijednosti naprezanja i deformacija kojima je materijal bokova zuba

4. CONCLUSION

The mesh of involute gears, through which motion and power are transmitted, is very complex. Stresses and strains in the teeth flanks material and its durability are influenced by a large number of factors such as gearing zupčanika u radu podvrgnut te na njegovu trajnost izravno utječu geometrija ozubljenja, kinematika zahvata, vrsta i vrijednost opterećenja, značajke materijala i površine bokova, uvjeti podmazivanja te niz drugih veličina, koje sve zajedno definiraju uvjete u kojima se odvija zahvat zupčanika.

Osim navedenog, za korektno i uspješno konstruiranje i dimenzioniranje zupčanika, posebice s obzirom na trajnost, potrebno je dobro poznavati i moguća oštećenja te mehanizme koji dovode do njihovog nastanka. U tom smislu u ovom radu opisane osnovne značajke kotrljajno-klizno-kontaktnog zamora materijala boka zuba zupčanika te uzroci pojave i značajke s njim povezanih oštećenja mogu poslužiti kao pomoć pri sprečavanju ili naknadnoj identifikaciji i uklanjanju potencijalnih problema kod zupčastih prijenosnika snage.

geometry, mesh kinematics, loading type and its magnitude, material and surface characteristics and lubrication conditions. Together, these influences define the conditions in which gears operate.

Apart from these meshing conditions, for a successful design and dimensioning of gears - particularly with regard to their durability - the types of damage and mechanisms by which they develop must also be known and taken into consideration. In this regard, the main features of rolling-sliding-contact fatigue of gear teeth flanks as well as corresponding damage types and their main causes have been described in this paper. The information presented can be used for prevention or subsequent identification and remedial action in the case of fatigue damage of gears in power transmissions.

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Pregledni članak

Subject review

Adresa autora / Authors' address
doc. dr. sc. Robert Basan, dipl. ing.
doc. dr. sc. Marina Franulović, dipl. ing.
red. prof. dr. sc. Božidar Križan, dipl. ing.
Tehnički fakultet Sveučilišta u Rijeci
Vukovarska 58
51000 Rijeka
HRVATSKA

Dipl. Ing. Dr. Markus Lengauer
Department of Automotive Engineering
FH JOANNEUM - University of applied sciences
Alte Poststrasse 149
8020 Graz
AUSTRIA