

UČNI NAČRT PREDMETA / COURSE SYLLABUS

Predmet:	Mehanika kontakta in tribologija
Course title:	Contact mechanics and tribology

Študijski program <i>Study programme and level</i>	Študijska smer <i>Study field</i>	Letnik <i>Academic year</i>	Semester <i>Semester</i>
Inženiring in avtomobilska industrija Podiplomski (tretja)	Program nima smeri	prvi	prvi
Engineering and Automotive Industry Graduate – Master (third)	The program has no study fields	First	First

Vrsta predmeta / Course type	Izbirni	Optional
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Univerzitetna koda predmeta / University course code:	DR_31022
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Predavanja <i>Lectures</i>	Seminar <i>Seminar</i>	Sem. vaje <i>Tutorial</i>	Lab. vaje <i>Laboratory work</i>	Teren. vaje <i>Field work</i>	Samost. delo <i>Individ. work</i>	ECTS
60		30			180	10

Nosilec predmeta / Lecturer:	prof. dr. Bojan Podgornik
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Jeziki / Languages:	Predavanja / Lectures:	Vaje / Tutorial:
	Slovenski	Slovenski
	Slovenian	Slovenian

Pogoji za vključitev v delo oz. za opravljanje študijskih obveznosti:

– Zaključena 2. stopnja študija, oz. magistrskega študijskega programa Inženiring in avtomobilska industrija, ali primerljivega programa.	Prerequisites: – Completed 2nd study level, i.e., the Masters degree Engineering and automotive industry, or a comparable program.
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Vsebina:

<ul style="list-style-type: none"> – Kontaktna površina: definicija, mehanske, fizikalne, kemijske in tribološke lastnosti, – Karakterizacija kontaktne površine: mikroskopija, profilometrija in topografija, trdota, zaostale napetosti, oprijemljivost zaščitnega sloja, tribološke lastnosti – Elastičen kontakt dveh ukrivljenih površin: geometrija, sile, hitrosti in napetostno-deformacijsko polje; – Vpliv obremenitve na kontaktne napetosti: linijska, poleiptična, inverzna poleiptična in poljubna zvezna porazdelitev kontaktnega tlaka, normalna in tangencialna obremenitev; Hertzova teorija kontakta: 	<p>Content (Syllabus outline):</p> <ul style="list-style-type: none"> – Contact surface: definition, mechanical, physical, chemical and tribological properties – Contact surface characterization: microscopy, profilometry and topography, hardness, residual stresses, adhesion, friction and wear – Elastic contact: geometry, forces, tangential load, deformation and stress field – Effect of load on contact stresses: line, semielliptical, inverse semielliptical and arbitrary distribution of contact pressure, normal and tangential load, Hertz contact theory – Stress analysis of sliding contact: unidirectional sliding, reciprocating sliding, micro and macro slip, rolling, elasto-plastic contact, elastic deformation,
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<ul style="list-style-type: none"> – Napetostna analiza kontakta pri gibanju: enosmerno drsenje, izmehično drsenje, mikro in makro zdrs, kotaljenje; Elasto-plastičen kontakt: elastična deformacija, plastična deformacija, vpliv tangencialne obremenitve, nosilnost površine – Kontakt hrapavih površin: vpliv mikro- in makro-hrapavost na porazdelitev napetostno-deformacijskega polja; Termoelastičen kontakt, termična nestabilnost kontakta; Interakcije med površino in okolico, površinska energija; kontakt eno in več-slojnih površin; – Izboljšanje triboloških lastnosti kontaktnih površin: namen, tehnike povečanja obrabne obstojnosti in znižanja trenja, priprava površine za nanos površinskih slojev, obličanje – Delitev, lastnosti in uporaba površinskih zaščitnih slojev – Smeri razvoja površinskih zaščitnih slojev: predpriprava podlage, duplex sistemi, večkomponentne prevleke, večplastne prevleke, diamantne in diamantu podobne prevleke – Vpliv lastnosti površinskega sloja na tribološke lastnosti kontaktnih površin: vpliv trdote, debeline, hrapavosti in temperature – Izbira postopka in praktični primeri uporabe obrabno obstojnih kontaktnih površin 	<p>plastic deformation, surface load-carrying capacity</p> <ul style="list-style-type: none"> – Contact of rough surfaces: effect of micro- and macro-roughness, thermo-elastic contact, thermal contact instability, surface interactions with environment, surface energy, contact of coated surfaces – Improving tribological properties of contact surfaces: aim, techniques, surface pre-treatment, surface texturing – Properties, types and use of hard protecting coatings – Trends in surface coatings: substrate pre-treatment, duplex treatments and systems, multi-composite coatings, multilayer coatings, diamond and diamond like carbon coatings – Effect of coating properties on friction and wear: effect of hardness, thickness, surface roughness and temperature – Selection of surface engineering technique and practical examples.
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Temeljna literatura in viri / Readings:

<ul style="list-style-type: none"> – Johnson, K.L. (1985). <i>Contact mechanics</i>. Cambridge University Press: Cambridge. – Bhushan, B., Gupta, B.K. (1991). <i>Handbook of tribology – Materials, Coatings and Surface Treatments</i>. McGraw-Hill: New York. – Holmberg, K. (2009). <i>Coatings Tribology</i>. Elsevier: Amsterdam. – Podgornik, B., Vižintin, J. (2010). <i>Mehanika kontakta, skripta</i>. Fakulteta za strojništvo: Univerza v Ljubljani. http://www2.arnes.si/~supbpodg/Mehanika_kontakta/Skripta/
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Priporočljiva literatura / Recommended Textbooks

<ul style="list-style-type: none"> – Iliuc, I. (1980). <i>Tribology of thin layers</i>. Elsevier: Amsterdam. – Stolarski, T.A. (1990). <i>Tribology in Machine Design</i>. Butterworth Heinemann: Oxford. – Bach, F.W., Laarmann, A., & Wenz, T. (2006). <i>Modern Surface Technology</i>. Wiley-vch: Weinheim. – Strafford, K.N., Datta, P.K., & Gray, J.S. (1990). <i>Surface engineering practice</i>. Ellis Horwood: New York. – Donnet, C., Erdemir, A. (2008). <i>Tribology of diamond-like carbon films : fundamentals and applications</i>. Springer: New York., 2008 – Stachowiak, G.W., Batchelor, A.W. (2013). <i>Engineering Tribology</i>. Butterworth: Heinemann.

Cilji in kompetence:

Objectives and competences:

<p>Cilji Cilj predmeta je seznaniti študente z osnovami kontaktnega problema dveh elastičnih ali plastičnih teles pri relativnem gibanju, porazdelitve sil, hitrosti, temperatur in kontaktnih napetosti na in pod površino tako v primeru enosmernega in izmeničnega drsenja, kakor tudi v primeru kotaljenja. Nadalje predstaviti tribološki kontakt, vključujoč mehanizme trenja, obrabe in določitve kritičnih mest za nastanek poškodb. Sledi seznanitev študentov z osnovnimi tribološkimi lastnostmi kontaktnih površin in možnosti povečanja obrabne obstojnosti, s poudarkom na pomembnosti in postopkih priprave podlage za nanos obrabno obstojnega sloja, ter vrstami in lastnostmi obrabno obstojnih površinskih slojev. Pri tem je poudarek na postopkih izbire parametrov in tehnike povečanja obrabne obstojnosti kontaktnih površin, lastnosti posameznih tehnik in njihovega vpliva na napetostno polje in tribološke lastnosti kontaktnih površin., ter predstaviti proces izboljšanja triboloških lastnosti kontaktne površine z uporabo ustreznih tehnik oplemenitenja kontaktne površine, osredotočene na pripravo podlage za nanos površinskih slojev, lastnosti površinskih slojev, mehanike slojevitih površin, potek izbire postopka oplemenitenja kontaktne površine, kakor tudi praktične primere uporabe.</p> <p>Kompetence</p> <ul style="list-style-type: none"> – Študent bo osvojil osnove analize kontakta pri enosmernem in izmeničnem drsenju ter kotaljenju, – Spoznal osnovne mehanizme trenja in obrabe – Znal določiti kritična mesta za nastanek poškodb na oz. pod kontaktno površino, – Osvojil proces načrtovanja izboljšanja odpornosti in triboloških lastnosti kontaktnih površin ter potek izbire postopka in parametrov oplemenitenja kontaktne površine glede na napetostno-deformacijsko polje. – Razumel bo pomen ustrezne priprave, obdelave in modificiranja površine za doseganje optimalnih lastnosti kontakta. 	<p>Objectives Objective of the course is to acquaint students with fundamentals for contact of two elastic or plastic bodies under relative motion (sliding and rolling), as well as surface and sub-surface distribution of deformation, stresses, speed and temperature. Furthermore, to introduce tribological contact, including mechanisms of friction and wear, and determination of critical areas for failure initiation. To define basic tribological properties of contact surfaces and review possibilities for improving surface wear resistance, emphasizing importance and procedure of substrate preparation, as well as types of wear resistant coatings. In terms of coatings, course is focused on proper selection of deposition technique and parameters, properties of different techniques and their effect on stress-strain field and tribological properties of the contact. Finally, complete process of surface engineering aimed at improving tribological properties of the contact will be presented and discussed, including substrate preparation, properties of different coatings, contact mechanics of coated surfaces and practical examples.</p> <p>Competences</p> <ul style="list-style-type: none"> – Student will master basics of contact analysis under unidirectional sliding, reciprocating sliding and rolling – understand friction and wear mechanisms – being able to define critical locations for failure initiation, on or below the contact surface – master process of improving tribological and wear properties of contact surfaces, including selection of parameters and surface engineering technique for given stress-strain conditions – Understand the importance of surface preparation, machining and modifying for optimal properties of the contact.
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Predvideni študijski rezultati:

Intended learning outcomes:

<p>Znanje in razumevanje: Študent pridobi:</p> <ul style="list-style-type: none"> – znanje o napetostno-deformacijskem polju v kontaktu dveh teles pri relativnem gibanju, o triboloških mehanizmih, vplivu trenja, obremenitvenega stanja in hrapavosti površine na velikost in lego maksimalnih napetosti ter postopkih izboljšanja odpornosti kontaktnih površin. – razumevanje proces nastanka poškodbe in izbire 	<p>Knowledge and understanding: Student will:</p> <ul style="list-style-type: none"> – acquire knowledge on stress-strain field in the case of two body contact under relative movement; tribological mechanisms; effect of friction, type of loading and surface roughness on magnitude and location of maximal shear stresses; processes for improving wear resistance of contact surfaces. – understand process of failure initiation and proper selection of surface engineering technique
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ustrezne tehnike oplemenitenja površine glede na napetostno-deformacijsko analizo kontakta ter vpliv parametrov oplemenitenja na mehanske in tribološke lastnosti kontaktnih površin.	depending on the stress-strain field analysis and effect on tribological properties of the contact.
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Metode poučevanja in učenja:

Learning and teaching methods:

<ul style="list-style-type: none"> – Predavanja učitelja(-ev) – Aktivno sodelovanje študentov na predavanjih. – Študentje rešujejo probleme na vajah. – Vodeni študij študentov na seminarskih/laboratorijskih vajah. – Uporaba tiskanega, elektronskega in internetnega gradiva. – Samostojno učenje študentov pri analizi kontaktnih problemov 	<ul style="list-style-type: none"> – Lectures. – Students active participation during lectures. – Students' problems solving in course work. – Guided students' studies during tutorial/lab work. – Use of paper, electronic and web resources. – Students self-learning in the modeling operations, of heat treatment, cementation and nitriding
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Načini ocenjevanja:

**Delež (v %) / Assessment:
Weight (in%)**

<ul style="list-style-type: none"> – pisni izpiti – ustni izpiti – laboratorijske in seminarske vaje – projekt 	<p>40</p> <p>10</p> <p>20</p> <p>30</p>	<ul style="list-style-type: none"> • written exam • oral exam • laboratory work • project
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Reference nosilca / Lecturer's references:

<p>Izvirni znanstveni članek</p> <ul style="list-style-type: none"> – VIŽINTIN, Jože, KALIN, Mitjan, PODGORNIK, Bojan, VODOPIVEC, Franc. The effect of slip amplitude and test time on fretting wear in metal-metal contact. Tribotest, ISSN 1354-4063, 1996, vol. 3, no. 2, str. 149-165. [COBISS.SI-ID 2140699] – VIŽINTIN, Jože, KALIN, Mitjan, PODGORNIK, Bojan, NOVAK, Saša. Comparison of the fretting wear of 100Cr6/100Cr6, Si3N4/Si3N4 and Si3N4/100Cr6 contacts in lubricated and dry conditions. Lubrication science, ISSN 0954-0075, 1997, 9, 4, str. 391-408. [COBISS.SI-ID 2145051] – PODGORNIK, Bojan, VIŽINTIN, Jože, LESKOVŠEK, Vojteh. Tribological properties of plasma and pulse plasma nitrided AISI 4140 steel. Surface & coatings technology, ISSN 0257-8972. [Print ed.], 1998, vol. 108/109, no. 1/3, str. 454-460. [COBISS.SI-ID 3033883] – PODGORNIK, Bojan, VIŽINTIN, Jože. Wear properties of plasma nitrided steel in dry conditions. Journal of tribology, ISSN 0742-4787, 1999, vol. 121, no. 4, str. 802-807. [COBISS.SI-ID 3352091] – PODGORNIK, Bojan, VIŽINTIN, Jože, LESKOVŠEK, Vojteh. Protiobrabne lastnosti jekla 42CrMo4, nitiranega v nepulzirajoči in pulzirajoči plazmi = Wear properties of plasma and pulse plasma nitrided 42CrMo4 steel. Kovine zlitine tehnologije, ISSN 1318-0010, 1999, letn. 33, št. 1/2, str. 51-54, ilustr. [COBISS.SI-ID 137898] – PODGORNIK, Bojan, VIŽINTIN, Jože, WÄNSTRAND, Olle, LARSSON, Mats, HOGMARK, Sture. Wear and friction behaviour of duplex-treated AISI 4140 steel. Surface & coatings technology, ISSN 0257-8972. [Print ed.], 1999, vol. 120/121, str. 502-508. [COBISS.SI-ID 3449883] – PEZDIRNIK, Jože, VIŽINTIN, Jože, PODGORNIK, Bojan. Temperatures at the interface and inside an oscillatory sliding microcontact - theoretical part. Tribology international, ISSN 0301-679X. [Print ed.], 1999, vol. 32, no.
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- 9, str. 481-489. [COBISS.SI-ID 3617563]
- PODGORNIK, Bojan, VIŽINTIN, Jože, LESKOVŠEK, Vojteh. Wear properties of induction hardened, conventional plasma nitrided and pulse plasma nitrided AISI 4140 steel in dry sliding conditions. *Wear*, ISSN 0043-1648. [Print ed.], 1999, vol. 232, no. 2, str. 231-242. [COBISS.SI-ID 3350555]
 - PODGORNIK, Bojan, VIŽINTIN, Jože, RONKAINEN, Helena, HOLMBERG, Kenneth. Wear resistance of DLC coating deposited on pretreated AISI 4140 steel. *Advanced engineering materials*, ISSN 1438-1656, 2000, vol. 2, no. 7, str. 444-448. [COBISS.SI-ID 4025627]
 - PODGORNIK, Bojan, VIŽINTIN, Jože, LESKOVŠEK, Vojteh, WÄNSTRAND, Olle, LARSSON, Mats, HOGMARK, Sture. Protiobrabne lastnosti jekla 42CrMo4 nitriranega v plazmi in prekritega s trdo zaščitno prevleko = Wear properties of plasma nitrided and hard coated 42CrMo4 steel. *Materiali in tehnologije*, ISSN 1580-2949. [Tiskana izd.], 2000, letn. 34, št. 1/2, str. 17-21, ilustr.; graf. prikazi. [COBISS.SI-ID 212138]
 - PODGORNIK, Bojan, VIŽINTIN, Jože, LESKOVŠEK, Vojteh, RONKAINEN, Helena, HOLMBERG, Kenneth. Tribološke lastnosti jekla nitriranega v plazmi in prekritega z DLC-prevleko = Tribological properties of DLC-coated plasma-nitrided steel. *Materiali in tehnologije*, ISSN 1580-2949. [Tiskana izd.], 2000, letn. 34, št. 6, str. 375-379. [COBISS.SI-ID 210015]
 - PODGORNIK, Bojan, VIŽINTIN, Jože, RONKAINEN, Helena, HOLMBERG, Kenneth. Friction and wear properties of DLC-coated plasma nitrided steel in unidirectional and reciprocating sliding. *Thin Solid Films*, ISSN 0040-6090. [Print ed.], 2000, vol. 377/378, issue 1/2, str. 254-260. <http://www.elsevier.nl/gej-ng/29/30/25/109/23/62/abstract.html>. [COBISS.SI-ID 4362011]
 - PODGORNIK, Bojan, VIŽINTIN, Jože. Tribological properties of plasma nitrided AISI 4140 steel under dry and lubricated sliding conditions. *Tribotest*, ISSN 1354-4063, 2000, vol. 6, no. 4, str. 357-371. [COBISS.SI-ID 3797019]
 - PODGORNIK, Bojan, VIŽINTIN, Jože. Influence of substrate treatment on the tribological properties of DLC coatings. *Diamond and related materials*, ISSN 0925-9635, 2001, vol. 10, no. 12, str. 2232-2237. <http://www.elsevier.com/gej-ng/10/16/45/46/38/49/abstract.html>, <http://www.sciencedirect.com/science/journal/09259635>. [COBISS.SI-ID 4867867]
 - PODGORNIK, Bojan, KALIN, Mitjan, VIŽINTIN, Jože, VODOPIVEC, Franc. Microstructural changes and contact temperatures during fretting in steel-steel contact. *Journal of tribology*, ISSN 0742-4787, 2001, vol. 123, no. 4, str. 670-675. [COBISS.SI-ID 4868891]
 - PODGORNIK, Bojan, VIŽINTIN, Jože. Wear resistance of pulse plasma nitrided AISI 4140 and A355 steels. *Materials Science & Engineering. A, Structural materials: Properties, Microstructure and Processing*, ISSN 0921-5093. [Print ed.], 2001, vol. A315, issue 1/2, str. 28-34. <http://www.elsevier.nl/cdweb/journals/09215093/viewer.htm?iss=1-2&vol315>. [COBISS.SI-ID 4502299]
 - PODGORNIK, Bojan, VIŽINTIN, Jože. Vpliv kemotermične obdelave podlage na tribološke lastnosti trdih prevlek = Influence of substrate pretreatment on the tribological properties of hard coatings. *Strojniški vestnik*, ISSN 0039-2480, 2001, letn. 47, št. 4, str. 152-162. [COBISS.SI-ID 4653083]
 - PODGORNIK, Bojan, VIŽINTIN, Jože, LESKOVŠEK, Vojteh. Obrabna odpornost konstrukcijskega jekla, nitriranega v plazmi = Wear resistance of plasma nitrided structural steel. *Strojniški vestnik*, ISSN 0039-2480, 2001, letn. 47, št. 4, str. 163-173. [COBISS.SI-ID 4653339]
 - PODGORNIK, Bojan. Coated machine elements - fiction or reality?. *Surface & coatings technology*, ISSN 0257-8972. [Print ed.], 2001, vol. 146/147, special issue "ICMCTF 2001", str. 318-323. <http://www.elsevier.nl/gej-ng/29/30/26/91/27/77/abstract.html>, <http://www.sciencedirect.com/science/journal/02578972>. [COBISS.SI-ID 4871707]
 - PODGORNIK, Bojan, VIŽINTIN, Jože. Sliding and pitting wear resistance of plasma and pulse plasma nitrided steel. *Surface engineering*, ISSN 0267-0844, 2001, vol. 17, no. 4, str. 300-304. [COBISS.SI-ID 4502555]
 - PODGORNIK, Bojan, VIŽINTIN, Jože, WÄNSTRAND, Olle, LARSSON, Mats, HOGMARK, Sture, RONKAINEN,

- Helena, HOLMBERG, Kenneth. Tribological properties of plasma nitrided and hard coated AISI 4140 steel. *Wear*, ISSN 0043-1648. [Print ed.], 2001, vol. 249, issue 3/4, str. 254-259. [COBISS.SI-ID 4502043]
- PODGORNIK, Bojan, VIŽINTIN, Jože. Rolling contact properties of ta-C coated low alloy steel. *Surface & coatings technology*, ISSN 0257-8972. [Print ed.], 2002, vol. 157, str. 257-261. [COBISS.SI-ID 5365275]
 - PODGORNIK, Bojan, VIŽINTIN, Jože. Tribology of thin films and their use in the field of machine elements. *Vacuum*, ISSN 0042-207X. [Print ed.], 2002, letn. 68, št. 1, str. 30-47. [COBISS.SI-ID 5504283]
 - PODGORNIK, Bojan, VIŽINTIN, Jože. Wear resistance of plasma and pulse plasma nitrided gears. *Gear technology*, ISSN 0743-6858, 2003, letn. 20, št. 2, str. 33-37. [COBISS.SI-ID 5647643]
 - ŠUŠTARŠIČ, Borivoj, KOSEC, Ladislav, DOLINŠEK, Slavko, PODGORNIK, Bojan. The characteristics of vacuum sintered M3/2 type HSSs -with MoS₂ addition. *Journal of materials processing technology*, ISSN 0924-0136. [Print ed.], 2003, vol. 143-144, str. 98-104. [COBISS.SI-ID 321450]
 - PODGORNIK, Bojan, JACOBSON, Staffan, HOGMARK, Sture. Influence of oil additives on the performance of DLC coatings = Vpliv aditivov na tribološke lastnosti prevlek na osnovi trdega ogljika. *Materiali in tehnologije*, ISSN 1580-2949. [Tiskana izd.], 2003, letn. 37, št. 1/2, str. 9-12. [COBISS.SI-ID 5819675]
 - PODGORNIK, Bojan, JACOBSON, S., HOGMARK, S. Influence of EP and AW additives on the tribological behaviour of hard low friction coatings. *Surface & coatings technology*, ISSN 0257-8972. [Print ed.], 2003, letn. 165, št. 2, str. 168-175. <http://www.sciencedirect.com/science/journal/02578972>. [COBISS.SI-ID 5576731]
 - PODGORNIK, Bojan, JACOBSON, Staffan, HOGMARK, Sture. DLC coating of boundary lubricated components- advantages of coating one of the contact surfaces rather than both or none. *Tribology international*, ISSN 0301-679X. [Print ed.], 2003, letn. 36, št. 11, str. 843-849. <http://www.sciencedirect.com/science/journal/0301679X>. [COBISS.SI-ID 6421787]
 - PODGORNIK, Bojan, HOGMARK, Sture, SANDBERG, O., LESKOVŠEK, Vojteh. Wear resistance and anti-sticking properties of duplex treated forming tool steel. *Wear*, ISSN 0043-1648. [Print ed.], 2003, letn. 254, str. 1113-1121. <http://www.sciencedirect.com/science/journal/00431648>. [COBISS.SI-ID 6411803]
 - PODGORNIK, Bojan, HOGMARK, Sture, SANDBERG, Odd. Možnosti uporabe trdih prevlek na preoblikovalnih orodjih = Wear and friction properties of hard coatings for forming tools. *Strojniški vestnik*, ISSN 0039-2480, 2004, letn. 50, št. 3, str. 148-156. [COBISS.SI-ID 7333147]
 - PODGORNIK, Bojan, VIŽINTIN, Jože, JACOBSON, Staffan, HOGMARK, Sture. Tribological behaviour of WC/C coatings operating under different lubrication regimes. *Surface & coatings technology*, ISSN 0257-8972. [Print ed.], 2004, letn. 177/178, str. 558-565. <http://www.sciencedirect.com/science/journal/02578972>. [COBISS.SI-ID 7108635]
 - PODGORNIK, Bojan, HOGMARK, Sture, SANDBERG, O. Influence of surface roughness and coating type on the galling properties of coated forming tool steel. *Surface & coatings technology*, ISSN 0257-8972. [Print ed.], 2004, letn. 184, št. 2/3, str. 338-348. <http://www.sciencedirect.com/science/journal/02578972>. [COBISS.SI-ID 7385883]
 - PODGORNIK, Bojan, JACOBSON, Staffan, HOGMARK, Sture. Influence of EP additive concentration on the tribological behaviour of DLC-coated steel surfaces. *Surface & coatings technology*, ISSN 0257-8972. [Print ed.], 2004, letn. 191, št. 2/3, str. 357-366. <http://www.sciencedirect.com/science/journal/02578972>. [COBISS.SI-ID 7808795]
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 - PODGORNIK, Bojan, WÄNSTRAND, Olle. An experimental method for coating-substrate interface investigation. *Materials characterization*, ISSN 1044-5803. [Print ed.], 2005, letn. 55, št. 3, str. 173-178. <http://dx.doi.org/10.1016/j.matchar.2005.04.011>. [COBISS.SI-ID 9556507]

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