CV of Prof. Ing. Michele Ciavarella (ENGLISH). April 2022

Main biographic data

Born in Bari in 1970, he graduates from Politecnico di BARI in Mech Eng in 1994 cum Laude and first of his cohort, and receives the PhD ("dottorato") in Mech Eng ("ingegneria dei sistemi avanzati di produzione) at Politecnico di BARI, spending most of his PhD time from March '96 to Aug.'97 at University of Oxford under Prof. DA Hills. In the mean time he has been Officer of the Italian Navy, and representative of all Italian office in the organism COCER by election.

From Oct. 1998 to Feb.1999 Senior Research Fellow (full time), University of Southampton, UK

From Feb 1999 - Ott 2002, Senior Researcher, Consiglio Nazionale delle Ricerche (Italian National Research Council), Bari, It. The youngest in Italy nominated to this senior position at age 28.

From Nov. 2002 to Nov.2017, Associate Professor at Politecnico di BARI (It), SSD Ing-Ind14 --- Machine Design. With Italian Habilitation to full professor in sector 09/A – Mechanical and aerospace engineering, obtained in 2014

Presently, and since nov. 2017, Full professor at Politecnico di BARI (It).

Included in the list of the Top Italian Scientists in Engineering (rank 121st) in the world
http://www.topitalianscientists.org/TIS_HTML/Top_Italian_Scientists_Engineering.htm

Ranked first by impact in the Ioannides Stanford ranking of Plos Biology in Politecnico di BARI, 4th in Italy in "mechanics", and 56 000th in the word in the entire set of 6 million researchers in SCOPUS.
,
From Oct.10 to Oct. 12, Humboldt Senior Research Fellow (6 months/year), Technical Univ. Hamburg Harburg (G), working on squeak on hip prosthesis

From Dec.07 to Sept 08 "Maitre de conférence" at Lab Mécanique des Solides Ecole Polytechnique Palaiseau(Fr) (sabbatical leave), working on fatigue models, corrugation of railways tracks,

From Jan. 2000 to Sept. 2006, Senior Research Fellow (part time), University of Southampton, UK

From Feb. 1998 to Aug.1998, Post-doc with Prof. D. A. Hills, University of Oxford, UK. Fretting fatigue and contact mechanics

From Jul. 1997 to Aug.1997, Research Fellow with Prof. JR Barber, University of Michigan, Ann Arbor USA. Thermoelastic instabilities in brakes and clutches

Conference organization

* Co-organizer of the world conference ICEM12 (Int Conf on Experimental Mechanics, www.icem12.poliba.it) in Bari, Italy, 29 Aug.-2 Sept. 2004.
* Co-organizer of the world conference Icf11 (International Congress on Fracture, www.icf11.com) in Torino, March 2005
* International Scientific Committee of the world conference Icf (International Congress on Fracture) 2009, 2013
* Co-organizer of the Italian conference on Fracture, in Bari, June 2000

Journal board memberships

- Member of Editorial Board of International Journal of Aerospace and Lightweight Structures (IJALS), from 2011-
- Member of Editorial Board of International Journal of Solids & Structures, from Sept. 05 to May 08.
- Member of Editorial Board of Fat Fract Eng Mat & Struct, from Feb. 07-Feb. 12.
- Member of Editorial Board of Acta Tribologica from Dec. 08-.
- Member of editorial board of Int J Mechanical Science, Elsevier, Impact factor 2.88, since 2017.
- Associate Editor Proc.

Administrative roles

- Rector's delegate for Politecnico di BARI for research with CNR (from 2010-2014)

Scientific commettees membership

- Member of International Scientific Commettee of CISIT - International Campus on Safety and Intermodality in Transportation, set in 2007 to address strategic aspects of transport in Nord Pas de Calais. This center groups 360 people, researchers, teachers, engineers, post-graduates, post-doctorates and assistants, and for 2007-2013 period, disposed of 46 M€ budget from various regional-state-european sources. Includes Ecole Centrale de Lille , Ecole des Mines de Douai, Université d'Artois, Université des Sciences et Technologies de Lille, Université de Valenciennes et du Hainaut-Cambrésis, IFFSTTAR, ONERA, and other research centers.
- International Panel member of Phd Programs in Mechanics at Ecole Centrale de Lille, Univ Valencia, Univ Sevilla, Politecnico di Torino

Research interests

His interests are in contact mechanics, adhesion, tribology, friction, wear, fatigue, fracture mechanics of elastic and viscoelastic media, corrugation of railways tracks, delamination and peeling.

H-index and other bibliometric data (on scopus)

Metrics overview

Documents by author 214
Citations 4705 by 3101 documents
Coauthors: 140
Topics: 12
h-index: 36

Participation in conferences
Has participated to many conferences of national and international standing, on the subjects of solid mechanics, fatigue, fracture, contact mechanics. He has taken part to almost all the editions of the Italian conference AIAS (from 1995), to various editions of the conference of the Italian Group of Fracture (IGF), to at least 2 International Congress of Fracture (ICF), etc.

Notable invited speeches at IMAC Conference and Exposition on Structural Dynamics 2014 ; 12th International Conference on Fracture 2009, ICF-12; ASME/STLE International Joint Tribology Conference, IJTC 2007; 11th International Conference on Fracture 2005, ICF11; ASME/STLE International Joint Tribology Conference, IJTC 2004; 2003 STLE/ASME Joint International Tribology Conference; Ponte Vedra Beach, FL; Fretting Fatigue: Advances in Basic Understanding and Applications; Nagaoka; Japan; 15 May 2001; The 2nd International Symposium on Fretting Fatigue: Current Technology and Practices; Salt Lake City, UT, USA; ; 31 August 1998 ; PACAM 1999

In particular, we remark invited lectures below.

Selection of special awards & invited lectures
* Invited visiting "maitre de conference" at Ecole Politechnique, Paris Palaiseau, Dec 07/Oct 2008
* Invited at NSF workshop on Friction modelling in Washington 14-15 Oct 2006
* Invitato at SNL/AWE/NSFInternational Workshop on JointMechanics, Dartington, UnitedKingdom, 27–29 April 2009
* Invited lecture at Thermo-mechanical modelling of solids – Ecole Politechnique, Paris Palaiseau 9-12 July 2007
* Invited by the US Air Force (*WOS Windows On Science* program) to a cycle of conferences on Fretting Fatigue at MIT (Prof. Subra Suresh), Purdue University (Prof. T. Farris), Wright Patterson AF Research Lab (Dr. Ted Nicholas), UC Berkeley (Prof. Robert Ritchie), February, 2000. For presenting the work on Fretting to the Universities and the labs connected to the MU(Multi University Research Initiative) of the USAF
* Invited by the Inst. of Physics (UK) to give a lecture at the workshop "Tribological Failure Mechanisms in Repeated Rolling Contacts" – Robinson College, Cambridge - 22 July 2003
* Invited by the Inst. of Physics (UK) to give a lecture at the workshop "Contact Mechanics", Bristol, march 2004
* 1998 Capocaccia National Prize of the Italian Stress Analysis Association (AIAS), for outstanding contribution to the study of frictional contact.
* CNR final prize after the grant spent in Feb. 1998 – August 1998 at University of Oxford, UK
*CNR "short term" fellowship travel grants: in July-August 1997, to University of Michigan, visiting Prof. JR Barber, in July-August 1999, to University of Oxford, visiting Prof. DA Hills, in July-August 2000, to University of Harvard, visiting Prof. JR Rice, in July-August 2001, to University of Oxford, visiting Dr. D. Nowell

Selection of grants

Centre of Excellence in Computational Mechanics* (CEMeC), from 2001--ongoing, as **co-PI and member of Managing Board (PI prof. Michele Napolitano). Also, Director of research line on "Thermoelastic and Fatigue contact problems", at Politecnico di Bari. Funded by Italian Minister for Research and Education with **750 kEu**. Popped up grant by Politecnico di Bari to 1MEu.

PROMOMAT project* on multiscale computational mechanics for hi/tech composite materials and coatings, involving a large number of companies and academic partners in Italy. 2002-ongoing. **PI, about **100 kEu**.

Research project of national interest (PRIN2004),* 2005-2006, on "Residual and multiaxial stress states in rolling contact fatigue problems", **PI, funded locally with **30.4kEu**

Vigoni project*, 2006-2007 as **PI with University of Hamburg and Stuttgard. Funded by DAAD and CRUI, with **5 kEu**.

**Galileo project* 2004/2005 Egide/ CRUI Conferenza dei Rettori, 2002, with Dr. Robert Wood & Dr. Singellakis (Univ. Southampton):- Optimisation and testing of surface protection coatings for hot components of turbines. Travel Grant. Funded for ≈US$ 5k.

AUTOCON - Brite Euram European Network Framework V Project on "Intermittency in Electrical Connectors"*, 2002-2006, **local PI, Coordinator: Dr. John McBride (Univ. Southampton). Funded locally with **100 kEu**.

*Network on COmputational MEchanics of Solids (COMES), CNR, PI, 1999-2001, ITL 40 ml. (≈**20kEu**). Funded.

*"Progetto Finalizzato Materiali Speciali per Tecnologie Avanzate II - PFMSTA II" **co/PI** with DPPI-Politecnico di Ba(Proff. Monno e Demelio), CNR, 1999-2000, ITL.29 ml. (≈**15kEu**).

Spin offs

*Co-founder of the "Polimech" small consulting spin-off company of Politecnico di BARI, dealing with various small projects with local companies.

Teaching activities

* 1999-2002 course on "Machine Design", University of Potenza (It)

* 2002- to date. Teaching 12 ECTS courses, generally 2 undergraduate (BSc) courses on "Machine Design" & "Mechanics and strength of Materials", and often 1 graduate course (MSc level) on "FEM in Mechanical Design". Politecnico di Bari (It). Has occasionally given courses in "Optimization methods", "Experimental mechanics".

* 2015- to date. Has been teaching at Phd level "Contact mechanics", and "Hands-on-Ansys".

Students thesis

More than 30 Master thesis, and about 10 Phd thesis (Paolo Decuzzi, Vito Tagarielli, Luciano Afferrante, Sonia di Bello (withdrawn), Cosmo Murolo, Carmine Putignano, Pietro D'Antuono), and collaboration with various phd thesis at U Michigan (Yun Bo Yi, Yong Hoon Jang) and U Oxford (P Blomerus, D Dini).

Some former students

D Dini, MSc 1999, presently Professor of Tribology at Imperial College UK Mechanical Engineering
L Afferrante, Phd 2003, presently Associate Professor, Politecnico di Bari, It
P. Decuzzi, Phd, 2002, presently Senior Researcher at Italian Institute of Technology
V Tagarielli, MSc 1999, presently Sen. Lecturer at Imperial College UK Aeronautical Engineering
A Cirilli, MSc 2001, presently CEO, Getrag, Mexico

F Giove, MSc 2002, presently director of R&D, CCValve, USA
A Papangelo, 2016, presently Associate Professor at Politecnico di BARI, with tenure.
Pietro D'Antuono, presently post-doc and spin-off manager, Bruxelles
And others

He is the only researcher in Italy that had 2 former phd students winning the most prestigious grant in Europe, ERC starting or consolidator Grant, Prof. Decuzzi and Prof. Papangelo, who has recently been appointed Associate Professor with tenure directly by Minister of Italian Research.

Key collaborations
Papers have been written in collaboration with collegues from Michigan U (Jim Barber), Oxford U (David Hills, David Nowell), Harvard U (Jim Rice, Joost Vlassak), Ecole Polytechnique (H.Maitournam, A. Constantinescu), Politecnico di Torino (Dino Chiaia, Nicola Pugno, Marco Paggi, and Alberto Carpinteri), Leicester U in UK (Alan Ponter), Università di Padova (Paolo Lazzarin), Università di Modena (Antonio Strozzi), Univ Hamburg (N. Hoffmann). Imperial College (D. Dini, V. Tagarielli), and many others.

Reviewing activities
Regular reviewer for journals in mechanical engineering, including • Tribology International • Wear • International Journal of Solids and Structures • International Journal of Mechanical Science • Journal of Mechanical Engineering Science • Applied Thermal Engineering • Tribology International • ASME - Journal of Tribology • Mathematical Problems in Engineering • Journal of Vibration and Control • Journal of Engineering Mathematics • Applications and Applied Mathematics • The Open Mechanics Journal

List of papers on international journals ISI (up to Jan 2021)
Scopus
EXPORT DATE:11 Jan 2021

Ciavarella, M.
Comments on old and recent theories and experiments of adhesion of a soft solid to a rough hard surface
(2021) Tribology International, 155, art. no. 106779, .
https://www.scopus.com/inward/record.uri?eid=2-s2.0-85097218571&doi=10.1016%2fj.triboint.2020.106779&partnerID=40&md5=bf36d34e8b3b4a01590ef9b3a6abadec

DOI: 10.1016/j.triboint.2020.106779
ABSTRACT: The old asperity model of Fuller and Tabor had demonstrated almost 50 years ago surprisingly good correlation with respect to quite a few experiments on the pull-off decay due to roughness of rubber spheres against roughened Perspex plates. We revisit here some features of the Fuller and Tabor model in view of the more recent theories and experiments, finding good correlation can be obtained only at intermediate resolutions, as perhaps in stylus profilometers. In general we confirm qualitatively the predictions of the Persson & Tosatti and Bearing Area Model of Ciavarella, as stickiness depends largely on the long wavelength content of roughness, and not the fine features. © 2020 Elsevier Ltd

Zaza, D., Ciavarella, M., Zurlo, G.
Strain incompatibility as a source of residual stress in welding and additive manufacturing
(2021) European Journal of Mechanics, A/Solids, 85, art. no. 104147, .

https://www.scopus.com/inward/record.uri?eid=2-s2.0-85093660890&doi=10.1016%2fj.euromechsol.2020.104147&partnerID=40&md5=fac058239b6d8a0005157074ed5177dc

DOI: 10.1016/j.euromechsol.2020.104147
ABSTRACT: The accumulation of residual stress during welding and additive manufacturing is an important effect that can significantly anticipate the workpiece failure. In this work we exploit the physical and analytical transparency of a 1.5D model to show that the deposition of thermally expanded material onto an elastic substrate leads to the accumulation of strain incompatibility. This field, which is the source of residual stress in the system, introduces memory of the construction history even in the absence of plastic deformations. The model is then applied to describe the onset and the progression of residual stresses during deposition, their evolution upon cooling, and the fundamental role played by the velocity of the moving heat source. © 2020 Elsevier Masson SAS

Papangelo, A., Lovino, R., Ciavarella, M.
Electroadhesive sphere-flat contact problem: A comparison between DMT and full iterative finite element solutions
(2020) Tribology International, 152, art. no. 106542, . Cited 1 time.
https://www.scopus.com/inward/record.uri?eid=2-s2.0-85089285606&doi=10.1016%2fj.triboint.2020.106542&partnerID=40&md5=391c5f26cb5a71f27a14aaacc3f26509

DOI: 10.1016/j.triboint.2020.106542
ABSTRACT: The electroadhesive contact between a conductive sphere with a rigid substrate, both coated with an electrically insulating layer is studied, by adopting two solution strategies: (i) a DMT approximation and (ii) an iterative finite element model which accounts for the effect of the electroadhesive tractions on the deformation of the elastic solids. The contact problem is solved by varying the applied voltage and the elastic modulus of the coating layer. The two approaches (i) and (ii) give comparable results only in the limit of very low applied voltage, while they differ quantitatively and qualitatively at high voltage, as the DMT approach largely fails in predicting the repulsive contact force, which leads to greatly overestimate the macroscopic adhesive force. © 2020 Elsevier Ltd

Papangelo, A., Cricrì, G., Ciavarella, M.
On the effect of the loading apparatus stiffness on the equilibrium and stability of soft adhesive contacts under shear loads
(2020) Journal of the Mechanics and Physics of Solids, 144, art. no. 104099, . Cited 1 time.
https://www.scopus.com/inward/record.uri?eid=2-s2.0-85088637685&doi=10.1016%2fj.jmps.2020.104099&partnerID=40&md5=ba7f2f61a9d06437a3b75b62b428d0f7

DOI: 10.1016/j.jmps.2020.104099
ABSTRACT: The interaction between contact area and frictional forces in adhesive soft contacts is receiving much attention in the scientific community due to its implications in many areas of engineering such as surface haptics and bioinspired adhesives. In this work, we consider a soft adhesive sphere that is pressed against a rigid substrate and is sheared by a tangential force where the loads are transferred to the sphere through a normal and a tangential spring, representing the loading apparatus stiffness. We derive a general linear elastic fracture mechanics solution, taking into account also the interaction between modes, by adopting a simple but effective mixed-mode model that has been recently validated against experimental results in similar problems. We discuss how the spring stiffness affects the stability of the equilibrium contact solution, i.e. the transition to separation or to sliding. © 2020 Elsevier Ltd

Papangelo, A., Ciavarella, M.

A numerical study on roughness-induced adhesion enhancement in a sphere with an axisymmetric sinusoidal waviness using Lennard-Jones interaction law
(2020) Lubricants, 8 (9), art. no. 90, . Cited 1 time.
https://www.scopus.com/inward/record.uri?eid=2-s2.0-85091713900&doi=10.3390%2fLUBRICANTS8090090&partnerID=40&md5=7045adab5251d72a0f5c1ad581dd35e0

DOI: 10.3390/LUBRICANTS8090090
ABSTRACT: Usually, roughness destroys adhesion and this is one of the reasons why the "adhesion paradox", i.e., a "sticky Universe", is not real. However, at least with some special type of roughness, there is even the case of adhesion enhancement, as it was shown clearly by Guduru, who considered the contact between a sphere and a wavy axisymmetric single scale roughness, in the limit of short-range adhesion (JKR limit). Here, the Guduru's problem is numerically solved by using the Boundary Element Method (BEM) with Lennard-Jones interaction law, which allowed us to explore the contact solution from the rigid to the JKR limit. It is shown that adhesion enhancement stops either for low Tabor parameter, or by large waviness amplitudes, due to the appearance of internal cracks within the contact patch. We do not seem to find a clear threshold for "stickiness" (complete elimination of adhesion), contrary to other recent theories on random roughness. The enhancement effect is well captured by an equation in terms of the Johnson parameter derived by Ciavarella-Kesari-Lew, and is much larger than the Persson-Tosatti enhancement in terms of increase of real contact area due to roughness. The Persson-Tosatti energetic argument for adhesion reduction seems to give a lower bound to the effective work of adhesion.

Ciavarella, M., Papangelo, A.
On the Degree of Irreversibility of Friction in Sheared Soft Adhesive Contacts
(2020) Tribology Letters, 68 (3), art. no. 81, . Cited 1 time.
https://www.scopus.com/inward/record.uri?eid=2-s2.0-85088450310&doi=10.1007%2fs11249-020-01318-5&partnerID=40&md5=c2aded476782d8752cb08f97d054d5e2

DOI: 10.1007/s11249-020-01318-5
ABSTRACT: A number of authors have experimentally assessed the influence of friction on adhesive contacts, and generally the contact area has been found to decrease due to tangential shear stresses at the interface. The decrease is however generally much smaller than that predicted already by the Savkoor and Briggs 1977 classical theory using “brittle” fracture mechanics mixed mode model extending the JKR (Griffith like) solution to the contact problem. The Savkoor and Briggs theory has two strong assumptions, namely that (i) shear tractions are also singular at the interface, whereas they have been found to follow a rather constant distribution, and that (ii) no dissipation occurs in the contact. While assumption (ii) has been extensively discussed in the Literature the role of assumption (i) remained unclear. We show that assuming entirely reversible slip at the interface with a constant shear stress fracture mechanics model leads to results almost indistinguishable from the Savkoor and Briggs model (and further in disagreement with experiments), hence it is assumption (ii) that critically affects the results. We analyze a large set of experimental data from Literature and show that the degree of irreversibility of friction can vary by orders of magnitude, despite similar materials and geometries, depending on the velocity at which the tangential load is applied.

Qiao, Y., Ciavarella, M., Yi, Y.-B., Wang, T.
Effect of wear on frictionally excited thermoelastic instability: A finite element approach
(2020) Journal of Thermal Stresses, 43 (12), pp. 1564-1576.

https://www.scopus.com/inward/record.uri?eid=2-s2.0-85088857297&doi=10.1080%2f01495739.2020.1792379&partnerID=40&md5=3de9d2eadfe8863213213ff60c76391a

DOI: 10.1080/01495739.2020.1792379
ABSTRACT: A finite element model for the effect of wear on thermoelastic instability (TEI) is developed by combining the equations of thermoelasticity, the classical wear law, along with the conforming contact conditions. The method is based on a two-dimensional, frictional sliding model with a bimaterial interface and a simplified geometry of finite thickness. An assumption of the solution in the perturbation form leads to a quadratic eigenvalue problem. The existing analytical solutions for two half planes are employed to validate the numerical solutions for several representative scenarios, including a limiting case in the absence of wear. The analytical solutions are also sought for the special cases when one of the materials is a nonconductor and when the two materials are identical, for the purpose of comparison. In general, good agreements between the numerical and analytical approaches have been obtained. However, the discrepancies exist when the wear rates of the two materials are close to each other and when the wear rates are significantly greater than the critical rate. It is confirmed through this study that wear may suppress or amplify the effect of TEI depending on the thermomechanical properties of the materials, which is consistent with the recent research findings on the same topic via an analytical approach. © 2020 Taylor & Francis Group, LLC.

Ciavarella, M.
Universal features in “stickiness” criteria for soft adhesion with rough surfaces
(2020) Tribology International, 146, art. no. 106031, . Cited 5 times.
https://www.scopus.com/inward/record.uri?eid=2-s2.0-85074323097&doi=10.1016%2fj.triboint.2019.106031&partnerID=40&md5=28990343dd0d89c02fcd358a6807b094

DOI: 10.1016/j.triboint.2019.106031
ABSTRACT: A very interesting recent paper by Dalvi et al. has demonstrated convincingly with adhesion experiments of a soft material with a hard rough material that the simple energy idea of Persson and Tosatti works reasonably well, namely the reduction in apparent work of adhesion is equal to the energy required to achieve conformal contact. We demonstrate here that, in terms of a stickiness criterion, this is extremely close to a criterion we derive from BAM (Bearing Area Model) of Ciavarella, and not very far from that of Violano et al. It is rather surprising that all these criteria give very close results and this also confirms stickiness to be mainly dependent on macroscopic quantities. © 2019 Elsevier Ltd

D'Antuono, P., Ciavarella, M.
Mean stress effect on Gaßner curves interpreted as shifted Wöhler curves and application to smooth and notched geometries
(2020) Fatigue and Fracture of Engineering Materials and Structures, 43 (4), pp. 818-830.
https://www.scopus.com/inward/record.uri?eid=2-s2.0-85080826743&doi=10.1111%2fffe.13197&partnerID=40&md5=0e7baac9d4ecc11da80be98b01650ee1

DOI: 10.1111/ffe.13197
ABSTRACT: Recently, the authors proposed the simple idea that Gaßner curves can be interpreted as shifted Wöhler curves if the Palmgren-Miner rule is applied. The idea is extended here to the general case of nonzero mean stress fatigue loading applied to smooth or notched specimens. The mean stress effect has been addressed through the corrections proposed by Smith-Watson-Topper and by Walker. In this way, a new expression for the shift factor G has been obtained. Through the application of the theory of the critical distances in its point variant,

G is demonstrated to be valid for both smooth and notched geometries. A comparison with the Society of Automotive Engineers (SAE) Keyhole test program data is added to substantiate the findings. © 2020 Wiley Publishing Ltd.

Ciavarella, M., Papangelo, A., Barber, J.R.
Effect of Wear on the Evolution of Contact Pressure at a Bimaterial Sliding Interface
(2020) Tribology Letters, 68 (1), art. no. 27, . Cited 1 time.
https://www.scopus.com/inward/record.uri?eid=2-s2.0-85078308499&doi=10.1007%2fs11249-020-1269-1&partnerID=40&md5=0a57bf87306ba69ef7c70114e72e0911

DOI: 10.1007/s11249-020-1269-1
ABSTRACT: The eigenfunction method pioneered by Galin (J Appl Math Mech 40: 981–986, 1976) is extended to provide a general solution to the transient evolution of contact pressure and wear of two sliding elastic half-planes, under the assumption that there is full contact and that the Archard–Reye wear law applies. The governing equations are first developed for sinusoidal profiles with exponential growth rates. The contact condition and the wear law lead to a characteristic equation for the growth rate and more general solutions are developed by superposition. The case of general initial profiles can then be written down as a Fourier integral. Decay rates increase with wavenumber, so fine-scale features are worn away early in the process. Qualitative features of the problem are governed by two dimensionless wear coefficients, which for many material combinations are small compared with unity. If one of the bodies does not wear and is non-plane, the system evolves to a non-trivial steady state in which the wearing body acquires a profile which migrates over its surface. © 2020, Springer Science+Business Media, LLC, part of Springer Nature.

Papangelo, A., Ciavarella, M.
The effect of wear on ThermoElastic Instabilities (TEI) in bimaterial interfaces
(2020) Tribology International, 142, art. no. 105977, . Cited 2 times.
https://www.scopus.com/inward/record.uri?eid=2-s2.0-85072729130&doi=10.1016%2fj.triboint.2019.105977&partnerID=40&md5=b3532016ea98e8f08504e7fd5fb52bd1

DOI: 10.1016/j.triboint.2019.105977
ABSTRACT: There is ample evidence of ThermoElastic Instabilities (TEI) occurring in sliding contacts. The very first experiments of JR Barber in 1969 suggested wear interacts in the process of localization of contact into “hot spots”. However, studies on the interaction of TEI with wear are scarce. We consider the case of two sliding halfspaces and make a perturbation analysis permitting the formation of waves migrating over the two bodies, in presence of wear. We find that for exactly identical bodies wear does not affect the stability boundary. In the other limit case of bad conductor against a good conductor, wear tends to suppress TEI completely. Intermediate cases show a complex range of possible effects: for certain thermomechanical properties wear may even reduce the critical speed. © 2019 Elsevier Ltd

Ciavarella, M., Cricrì, G.
On the application of fracture mechanics mixed-mode models of sliding with friction and adhesion
(2020) Bioinspiration and Biomimetics, 15 (1), art. no. 015003, . Cited 1 time.
https://www.scopus.com/inward/record.uri?eid=2-s2.0-85075813350&doi=10.1088%2f1748-3190%2fAB53C0&partnerID=40&md5=17cc0aea2cf927d6401a393528404b8d

DOI: 10.1088/1748-3190/AB53C0
ABSTRACT: As recently suggested in an interesting and stimulating paper by Menga, Carbone and Dini (MCD), applying fracture mechanics energy concepts for the case of a sliding adhesive contact, imposing also the shear

stress is constant at the interface and equal to a material constant (as it seems in experiments), leads to a increase of contact area which instead is never observed. We add that the MCD theory also predicts a size effect and hence a distortion of the JKR curve during sliding which is also not observed in experiments. Finally, a simpler example with the pure mode I contact case, leads in the MCD theory to an unbounded contact area, rather than a perhaps more correct limit of the Maugis-Dugdale solution for the adhesive sphere when Tabor parameter is zero, that is DMT's solution. We discuss that the MCD theory does not satisfy equilibrium, and we propose some more correct formulations, although they may be rather academic: Recent semi-empirical models, with an appropriate choice of the empirical parameters, seem more promising and robust in modelling actual experiments.

Argatov, I., Papangelo, A., Ciavarella, M.
Elliptical adhesive contact under biaxial stretching
(2020) Proceedings of the Royal Society A: Mathematical, Physical and Engineering Sciences, 476 (2233), art. no. 20190507, . Cited 2 times.
https://www.scopus.com/inward/record.uri?eid=2-s2.0-85079666474&doi=10.1098%2frspa.2019.0507&partnerID=40&md5=3035fdfd870523ef14703d7e7d6e81ca

DOI: 10.1098/rspa.2019.0507
ABSTRACT: Adhesive contact of the Hertzian indenter with an incompressible elastic substrate bi-directionally stretched along the indenter principal planes of curvature is considered in the Johnson–Kendall–Roberts theoretical framework. An approximate model is constructed by examining energy release rate conditions only on the edges of the minor and major axes of the contact ellipse. The effect of weak coupling between fracture modes I and II is introduced using a phenomenological mode-mixity function. This study was motivated by the need to model a passive–adhesive mechanism in cell mechanics on stretchable substrates.

Genovese, A., Carputo, F., Ciavarella, M., Farroni, F., Papangelo, A., Sakhnevych, A.
Analysis of multiscale theories for viscoelastic rubber friction
(2020) Lecture Notes in Mechanical Engineering, pp. 1125-1135. Cited 1 time.
https://www.scopus.com/inward/record.uri?eid=2-s2.0-85083988850&doi=10.1007%2f978-3-030-41057-5_91&partnerID=40&md5=a95121b30c91265b59378063256e13a3

DOI: 10.1007/978-3-030-41057-5_91
ABSTRACT: Rubber friction plays a fundamental role in the study of the tire-road interaction and still represents a topic of discussion for both academics and manufacturing companies, especially with the introduction of the concept of multiscale roughness [1, 2]. Taking into account that the road surface is a hard substrate, the two contributions to rubber friction can be considered to be (i) hysteretic phenomena deriving from time dependent viscoelastic deformations of the rubber due to the substrate asperities and (ii) adhesive effects. From the modelling point of view, the estimation of each contribution represents a great challenge, and both formulations are inevitably affected by the presence of empirical constants. For example, hysteretic friction could be in principle computed by a full multiscale Persson's theory [1, 3], but the latter one ultimately embraces an arbitrary choice of the cutoff frequency value, and, furthermore, the full multiscale theory can be in most cases simplified [4]. The adhesive contribution, instead, remains fundamentally empirically described by fitting functions and parameters, and, despite considerable progress and huge effort in this research field, it continues to represent the greatest challenge as well as to recognize the relative importance of the two contributions [5]. In this work, an analysis of the results obtained with the different formulations available in literature is proposed with particular reference to the empirical constants variability.

D'Antuono, P., Ciavarella, M.
Citation doping not for Italy's elites
(2019) Nature, 574 (7778), p. 333.
https://www.scopus.com/inward/record.uri?eid=2-s2.0-85073406439&doi=10.1038%2fd41586-019-03119-w&partnerID=40&md5=795772c9a25fb7c9e16f14e358a9e563

DOI: 10.1038/d41586-019-03119-w

Genovese, A., Farroni, F., Papangelo, A., Ciavarella, M.
A discussion on present theories of rubber friction, with particular reference to different possible choices of arbitrary roughness cutoff parameters
(2019) Lubricants, 7 (10), art. no. 85, . Cited 5 times.
https://www.scopus.com/inward/record.uri?eid=2-s2.0-85074530862&doi=10.3390%2flubricants7100085&partnerID=40&md5=5b3f59e6bf487a86890413f7960c7397

DOI: 10.3390/lubricants7100085
ABSTRACT: Since the early study by Grosch in 1963 it has been known that rubber friction shows generally two maxima with respect to speed-the first one attributed to adhesion, and another at higher velocities attributed to viscoelastic losses. The theory of Klüppel and Heinrich and that of Persson suggests that viscoelastic losses crucially depend on the "multiscale" aspect of roughness and in particular on truncation at fine scales. In this study, we comment a little on both theories, giving some examples using Persson's theory on the uncertainties involved in the truncation of the roughness spectrum. It is shown how different choices of Persson's model parameters, for example the high-frequency cutoff, equally fit experimental data on viscoelastic friction, hence it is unclear how to rigorously separate the adhesive and the viscoelastic contributions from experiments. © 2019 by the authors.

Didonna, M., Stender, M., Papangelo, A., Fontanela, F., Ciavarella, M., Hoffmann, N.
Reconstruction of governing equations from vibration measurements for geometrically nonlinear systems
(2019) Lubricants, 7 (8), art. no. 64, .
https://www.scopus.com/inward/record.uri?eid=2-s2.0-85071170792&doi=10.3390%2flubricants7080064&partnerID=40&md5=7f8ac71a2797231961e490d0e15d83d0

DOI: 10.3390/lubricants7080064
ABSTRACT: Data-driven system identification procedures have recently enabled the reconstruction of governing differential equations from vibration signal recordings. In this contribution, the sparse identification of nonlinear dynamics is applied to structural dynamics of a geometrically nonlinear system. First, the methodology is validated against the forced Duffing oscillator to evaluate its robustness against noise and limited data. Then, differential equations governing the dynamics of two weakly coupled cantilever beams with base excitation are reconstructed from experimental data. Results indicate the appealing abilities of data-driven system identification: underlying equations are successfully reconstructed and (non-)linear dynamic terms are identified for two experimental setups which are comprised of a quasi-linear system and a system with impacts to replicate a piecewise hardening behavior, as commonly observed in contacts. © 2019 by the authors.

Acito, V., Ciavarella, M., Prevost, A.M., Chateauminois, A.
Adhesive Contact of Model Randomly Rough Rubber Surfaces
(2019) Tribology Letters, 67 (2), art. no. 54, . Cited 2 times.
https://www.scopus.com/inward/record.uri?eid=2-s2.0-85064013251&doi=10.1007%2fs11249-019-1164-9&partnerID=40&md5=96a23861de7e7a60fd00d76a9d81ba6d

DOI: 10.1007/s11249-019-1164-9
ABSTRACT: We study experimentally and theoretically the equilibrium adhesive contact between a smooth glass lens and a rough rubber surface textured with spherical microasperities with controlled height and spatial distributions. Measurements of the real contact area A versus load P are performed under compression by imaging the light transmitted at the microcontacts. A(P) is found to be non-linear and to strongly depend on the standard deviation of the asperity height distribution. Experimental results are discussed in the light of a discrete version of Fuller and Tabor's (FT) original model (Proc R Soc A 345:327, 1975), which allows to take into account the elastic coupling arising from both microasperities interactions and curvature of the glass lens. Our experimental data on microcontact size distributions are well captured by our discrete extended model. We show that the elastic coupling arising from the lens curvature has a significant contribution to the A(P) relationship. Our discrete model also clearly shows that the adhesion-induced effect on A remains significant even for vanishingly small pull-off forces. Last, at the local asperity length scale, our measurements show that the pressure dependence of the microcontacts density can be simply described by the original FT model.

Papangelo, A., Scheibert, J., Sahli, R., Pallares, G., Ciavarella, M.
Shear-induced contact area anisotropy explained by a fracture mechanics model
(2019) Physical Review E, 99 (5), art. no. 053005, . Cited 14 times.
https://www.scopus.com/inward/record.uri?eid=2-s2.0-85066449824&doi=10.1103%2fPhysRevE.99.053005&partnerID=40&md5=c7a1328894d57195161306dc5f0de577

DOI: 10.1103/PhysRevE.99.053005
ABSTRACT: This paper gives a theoretical analysis for the fundamental problem of anisotropy induced by shear forces on an adhesive contact, discussing the experimental data of the companion Letter. We present a fracture mechanics model where two phenomenological mode-mixity functions are introduced to describe the weak coupling between modes I and II or I and III, which changes the effective toughness of the interface. The mode-mixity functions have been interpolated using the data of a single experiment and then used to predict the behavior of the whole set of experimental observations. The model extends an idea by Johnson and Greenwood, to solve purely mode I problems of adhesion in the presence of a nonaxisymmetric Hertzian geometry, to the case of elliptical contacts sheared along their major or minor axis. Equality between the stress intensity factors and their critical values is imposed solely at the major and minor axes. We successfully validate our model against experimental data. The model predicts that the punch geometry will affect both the shape and the overall decay of the sheared contact area.

Sahli, R., Pallares, G., Papangelo, A., Ciavarella, M., Ducottet, C., Ponthus, N., Scheibert, J.
Shear-Induced Anisotropy in Rough Elastomer Contact
(2019) Physical Review Letters, 122 (21), art. no. 214301, . Cited 18 times.
https://www.scopus.com/inward/record.uri?eid=2-s2.0-85066433512&doi=10.1103%2fPhysRevLett.122.214301&partnerID=40&md5=f3862e1e5e30236ff3b84ad04bac4ef1

DOI: 10.1103/PhysRevLett.122.214301
ABSTRACT: True contact between randomly rough solids consists of myriad individual microjunctions. While their total area controls the adhesive friction force of the interface, other macroscopic features, including viscoelastic friction, wear, stiffness, and electric resistance, also strongly depend on the size and shape of individual microjunctions. We show that, in rough elastomer contacts, the shape of microjunctions significantly varies as a

function of the shear force applied to the interface. This process leads to a growth of anisotropy of the overall contact interface, which saturates in the macroscopic sliding regime. We show that smooth sphere-plane contacts have the same shear-induced anisotropic behavior as individual microjunctions, with a common scaling law over 4 orders of magnitude in the initial area. We discuss the physical origin of the observations in light of a fracture-based adhesive contact mechanics model, described in the companion article, which captures the smooth sphere-plane measurements. Our results shed light on a generic, overlooked source of anisotropy in rough elastic contacts, not taken into account in current rough contact mechanics models.

Ciavarella, M., Papangelo, A.
Extensions and comparisons of BAM (Bearing Area Model) for stickiness of hard multiscale randomly rough surfaces
(2019) Tribology International, 133, pp. 263-270. Cited 3 times.
https://www.scopus.com/inward/record.uri?eid=2-s2.0-85060352777&doi=10.1016%2fj.triboint.2018.10.001&partnerID=40&md5=6dd034aad710a7eafc342b422cf29f9d

DOI: 10.1016/j.triboint.2018.10.001
ABSTRACT: In the present paper, we consider a recent very simple model for the estimate of adhesion between elastic (hard) rough solids with Gaussian multiple scales of roughness (BAM, Bearing Area Model), and compare it in particular with very recent extensive results from the numerical method of Joe, Thouless and Barber (JTB theory), in the range of non-hysteretic behaviour. BAM shows no sensitiveness to rms slopes and curvatures for the pull-off load or the apparent surface energy, in agreement with the JTB theory, but in contrast with the criterion proposed by Pastewka and Robbins for stickiness, especially in the fractal limit. Results show also reasonable accuracy with the JTB theory, and BAM theory is simpler than that of Persson and Scaraggi which involves convolution of adhesion tractions in the regions of separation. © 2018 Elsevier Ltd

Tricarico, M., Papangelo, A., Constantinescu, A., Ciavarella, M.
On adhesive theories in multilayered interfaces, with particular regard to "surface force apparatus" geometry
(2019) Facta Universitatis, Series: Mechanical Engineering, 17 (1), pp. 95-102. Cited 1 time.
https://www.scopus.com/inward/record.uri?eid=2-s2.0-85064148174&doi=10.22190%2fFUME190118011T&partnerID=40&md5=c004a592253e4d189c234934bddb9f8b

DOI: 10.22190/FUME190118011T
ABSTRACT: Adhesion is a key factor in many tribological processes, especially wear. We generalize a recent formulation for the indentation of a multilayered material using an efficient integral transform method, to the case of adhesion, using a simple energetic transformation in the JKR regime. Then, we specialize the study for the geometry of the Surface Force Apparatus, which consists of two thin layers on a substrate, where the intermediate layer is softer than the other two. We find the pull-off force under "force control" (i.e. for "soft" loading systems), as well as under "displacement control" (i.e. for "rigid" systems), as a function of the geometrical thicknesses and material properties ratios, and the method is fully implemented in a fast Mathematica code, available to the public (see Appendix). © 2019 by University of Niš, Serbia.

Papangelo, A., Ciavarella, M.
On mixed-mode fracture mechanics models for contact area reduction under shear load in soft materials
(2019) Journal of the Mechanics and Physics of Solids, 124, pp. 159-171. Cited 15 times.
https://www.scopus.com/inward/record.uri?eid=2-s2.0-85055046525&doi=10.1016%2fj.jmps.2018.10.011&partnerID=40&md5=5e077e82c1dd32b70a103f00feda141a

DOI: 10.1016/j.jmps.2018.10.011

ABSTRACT: The fundamental problem of friction in the presence of macroscopic adhesion, as in soft bodies, is receiving interest from many experimentalists. Since the first fracture mechanics ‘purely brittle’ model of Savkoor and Briggs, models have been proposed where the mixed mode toughness is interpreted with phenomenological fitting coefficients introducing weaker coupling between modes than expected by the “purely brittle” model. We compare here two such previously proposed models and introduce a third one to show that the transition to sliding is very sensitive to the form of the mixed-mode model. In particular, after a quadratic decay of the contact area with load for modest tangential loads, depending on the exact form of the mixed mode function, there is an inflexion point and an asymptotic limit, or a jump to the Hertzian contact area. We find also that the unstable points are different under load or displacement control. Hence, the form of the mixed mode function, and not only its parameter, is an extremely sensitive choice. © 2018 Elsevier Ltd

Papangelo, A., Guarino, R., Pugno, N., Ciavarella, M.
On unified crack propagation laws
(2019) Engineering Fracture Mechanics, 207, pp. 269-276. Cited 2 times.
https://www.scopus.com/inward/record.uri?eid=2-s2.0-85059767936&doi=10.1016%2fj.engfracmech.2018.12.023&partnerID=40&md5=aba65d129b7e6f5e329d709793db6a67

DOI: 10.1016/j.engfracmech.2018.12.023
ABSTRACT: The anomalous propagation of short cracks shows generally exponential fatigue crack growth but the dependence on stress range at high stress levels is not compatible with Paris’ law with exponent m=2. Indeed, some authors have shown that the standard uncracked SN curve is obtained mostly from short crack propagation, assuming that the crack size a increases with the number of cycles N as [Formula presented]=HΔσha where h is close to the exponent of the Basquin's power law SN curve. We therefore propose a general equation for crack growth which for short cracks has the latter form, and for long cracks returns to the Paris’ law. We show generalized SN curves, generalized Kitagawa–Takahashi diagrams, and discuss the application to some experimental data. The problem of short cracks remains however controversial, as we discuss with reference to some examples. © 2018 Elsevier Ltd

Papangelo, A., Fontanela, F., Grolet, A., Ciavarella, M., Hoffmann, N.
Multistability and localization in forced cyclic symmetric structures modelled by weakly-coupled Duffing oscillators
(2019) Journal of Sound and Vibration, 440, pp. 202-211. Cited 9 times.
https://www.scopus.com/inward/record.uri?eid=2-s2.0-85055557914&doi=10.1016%2fj.jsv.2018.10.028&partnerID=40&md5=89bc7bc98e9f016374225361b65fc156

DOI: 10.1016/j.jsv.2018.10.028
ABSTRACT: Many engineering structures are composed of weakly coupled sectors assembled in a cyclic and ideally symmetric configuration, which can be simplified as forced Duffing oscillators. In this paper, we study the emergence of localized states in the weakly nonlinear regime. We show that multiple spatially localized solutions may exist, and the resulting bifurcation diagram strongly resembles the snaking pattern observed in a variety of fields in physics, such as optics and fluid dynamics. Moreover, in the transition from the linear to the nonlinear behaviour isolated branches of solutions are identified. Localization is caused by the hardening effect introduced by the nonlinear stiffness, and occurs at large excitation levels. Contrary to the case of mistuning, the presented localization mechanism is triggered by the nonlinearities and arises in perfectly homogeneous systems. © 2018 Elsevier Ltd

Ciavarella, M., Papangelo, A.
Some simple results on the multiscale viscoelastic friction

(2019) Facta Universitatis, Series: Mechanical Engineering, 17 (2), pp. 191-205.
https://www.scopus.com/inward/record.uri?eid=2-s2.0-85073288415&doi=10.22190%2fFUME190215025C&partnerID=40&md5=ca812771926c7d675a064b9a18ef58e2

DOI: 10.22190/FUME190215025C
ABSTRACT: The coefficient of friction due to bulk viscoelastic losses corresponding to multiscale roughness can be computed with Persson's theory. In the search for a more complete understanding of the parametric dependence of the friction coefficient, we show asymptotic results at low or large speed for a generalized Maxwell viscoelastic material, or for a material showing power law storage and loss factors at low frequencies. The ascending branch of friction coefficient at low speeds highly depends on the rms slope of the surface roughness (and hence on the large wave vector cutoff), and on the ratio of imaginary and absolute value of the modulus at the corresponding frequency, as noticed earlier by Popov. However, the precise multiplicative coefficient in this simplified equation depends in general on the form of the viscoelastic modulus. Vice versa, the descending (unstable) branch at high speed mainly on the amplitude of roughness, and this has apparently not been noticed before. Hence, for very broad spectrum of roughness, friction would remain high for quite few decades in sliding velocity. Unfortunately, friction coefficient does not depend on viscoelastic losses only, and moreover there are great uncertainties in the choice of the large wave vector cutoff, which affect friction coefficient by orders of magnitudes, so at present these theories do not have much predictive capability. © 2019 by University of Niš, Serbia.

Ciavarella, M., Xu, Y., Jackson, R.L.
The generalized Tabor parameter for adhesive rough contacts near complete contact
(2019) Journal of the Mechanics and Physics of Solids, 122, pp. 126-140. Cited 2 times.
https://www.scopus.com/inward/record.uri?eid=2-s2.0-85053786334&doi=10.1016%2fj.jmps.2018.08.011&partnerID=40&md5=93de6a4af7f412e6744c81775ef05882

DOI: 10.1016/j.jmps.2018.08.011
ABSTRACT: Recently, the first author has obtained a model for adhesive contact near full contact under the JKR assumptions. The model shows, in the common case of low fractal dimensions, an ‘unbounded’ adhesion enhancement when larger and larger upper “truncation wavenumber” is considered in the spectrum of roughness, i.e. when we increase “magnification”. Here, using a more general Maugis–Dugdale model, we show that a generalized multiscale Tabor parameter can be defined which shows a transition to a non-hysteretic regime, dependent on the root-mean-square (rms) slope of the surface. The contact area returns in the “fractal limit” to the adhesionless one. Two examples of rough surfaces from the literature are considered to show the full dependence on magnification of the adhesive solution. The choice of the truncation of the spectrum remains fundamentally arbitrary. © 2018 Elsevier Ltd

Violano, G., Afferrante, L., Papangelo, A., Ciavarella, M.
On stickiness of multiscale randomly rough surfaces
(2019) Journal of Adhesion, . Cited 8 times.
https://www.scopus.com/inward/record.uri?eid=2-s2.0-85074840890&doi=10.1080%2f00218464.2019.1685384&partnerID=40&md5=d31f9ff8f5fa4d9e2edf7fe6ce865660

DOI: 10.1080/00218464.2019.1685384
ABSTRACT: A new stickiness criterion for solids having random fractal roughness is derived using Persson’s theory with DMT-type adhesion. As expected, we find that stickiness, i.e. the possibility to sustain macroscopic tensile pressures or else non-zero contact area without load, is not affected by the truncation of the PSD spectrum

of roughness at short wavelengths and can persist up to roughness amplitude orders of magnitude larger than the range of attractive forces. With typical nanometre values of the latter, the criterion gives justification to the well-known empirical Dalhquist criterion for stickiness that demands adhesives to have elastic modulus lower than about 1 MPa. © 2019, © 2019 Taylor & Francis Group, LLC.

Ciavarella, M., Joe, J., Papangelo, A., Barber, J.R.
The role of adhesion in contact mechanics
(2019) Journal of the Royal Society Interface, 16 (151), art. no. 20180738, . Cited 29 times.
https://www.scopus.com/inward/record.uri?eid=2-s2.0-85062341227&doi=10.1098%2frsif.2018.0738&partnerID=40&md5=f255be1348a6aae21e697c7ca28ca921

DOI: 10.1098/rsif.2018.0738
ABSTRACT: Adhesive (e.g. van der Waals) forces were not generally taken into account in contact mechanics until 1971, when Johnson, Kendall and Roberts (JKR) generalized Hertz' solution for an elastic sphere using an energetic argument which we now recognize to be analogous to that used in linear elastic fracture mechanics. A significant result is that the load-displacement relation exhibits instabilities in which approaching bodies 'jump in' to contact, whereas separated bodies 'jump out' at a tensile 'pull-off force'. The JKR approach has since been widely used in other geometries, but at small length scales or for stiffer materials it is found to be less accurate. In conformal contact problems, other instabilities can occur, characterized by the development of regular patterns of regions of large and small traction. All these instabilities result in differences between loading and unloading curves and consequent hysteretic energy losses. Adhesive contact mechanics has become increasingly important in recent years with the focus on soft materials (which generally permit larger areas of the interacting surfaces to come within the range of adhesive forces), nano-devices and the analysis of bio-systems. Applications are found in nature, such as insect attachment forces, in nano-manufacturing, and more generally in industrial systems involving rubber or polymer contacts. In this paper, we review the strengths and limitations of various methods for analysing contact problems involving adhesive tractions, with particular reference to the effect of the inevitable roughness of the contacting surfaces. © 2019 The Author(s).

Ciavarella, M., Ahn, Y.J.
A note on the crack analogue fretting fatigue model with varying normal load
(2018) Acta Mechanica, 229 (12), pp. 4953-4961.
https://www.scopus.com/inward/record.uri?eid=2-s2.0-85055870235&doi=10.1007%2fs00707-018-2278-0&partnerID=40&md5=7b67ce82afbd25e8e4c570b7ef11415d

DOI: 10.1007/s00707-018-2278-0
ABSTRACT: The crack analogue model was developed to interpret various experimental observations of damage and cracking in fretting fatigue. This method assumes infinite friction at the interface and defines the oscillatory stress-intensity factor at the contact edge when the tangential load cyclically varies while the normal force is constant. However, practical engineering systems are subject to periodic loading in both the normal and shear directions, so that the contact area is not constant any more. Recently, Ciavarella and Berto suggested a crude extension to the crack analogue model in order to include the case of varying normal load, which is still not immediate to use since the singularities move in space and have no equivalent to fatigue from a crack. In this paper, we shall investigate the validity of the proposed model. For this, we shall establish an exact solution for a full stick contact problem with harmonic loading in normal and tangential directions. Here, this solution shows that there is a moving singularity at the edge of the contact area as unloading proceeds. The magnitude of the moving singularity depends on the tangential force difference between unloading and loading curve at constant normal force and the instantaneous value of the contact semi-width. Also, this solution shows that there is a logarithmic singularity which does not move. © 2018, Springer-Verlag GmbH Austria, part of Springer Nature.

Borri-Brunetto, M., Ciavarella, M.
Elastic indentation of a rough surface by a conical punch
(2018) Meccanica, 53 (13), pp. 3355-3364.
https://www.scopus.com/inward/record.uri?eid=2-s2.0-85050189528&doi=10.1007%2fs11012-018-0877-4&partnerID=40&md5=9d7a78a158c7232cbfe6541be9ce7bdd

DOI: 10.1007/s11012-018-0877-4
ABSTRACT: In the contact of a cone with a rough plane the mean pressure in the contact area is constant. In particular, above a critical ratio of the opening angle of the cone with respect to the rms gradient of surface roughness, the mean pressure is the same of that for nominally flat contact, no matter how large is the normal load. We introduce a new variable, namely, the local density of contact area, whose integral over the smooth nominal contact domain gives the real contact area. The results given by the theoretical model agree with the numerical simulations of the same problem presented in the paper. © 2018, Springer Nature B.V.

Vakis, A.I., Yastrebov, V.A., Scheibert, J., Nicola, L., Dini, D., Minfray, C., Almqvist, A., Paggi, M., Lee, S., Limbert, G., Molinari, J.F., Anciaux, G., Aghababaei, R., Echeverri Restrepo, S., Papangelo, A., Cammarata, A., Nicolini, P., Putignano, C., Carbone, G., Stupkiewicz, S., Lengiewicz, J., Costagliola, G., Bosia, F., Guarino, R., Pugno, N.M., Müser, M.H., Ciavarella, M.
Modeling and simulation in tribology across scales: An overview
(2018) Tribology International, 125, pp. 169-199. Cited 131 times.
https://www.scopus.com/inward/record.uri?eid=2-s2.0-85044579364&doi=10.1016%2fj.triboint.2018.02.005&partnerID=40&md5=c4c76cc075b1c339a02b6fcad96b2a7f

DOI: 10.1016/j.triboint.2018.02.005
ABSTRACT: This review summarizes recent advances in the area of tribology based on the outcome of a Lorentz Center workshop surveying various physical, chemical and mechanical phenomena across scales. Among the main themes discussed were those of rough surface representations, the breakdown of continuum theories at the nano- and microscales, as well as multiscale and multiphysics aspects for analytical and computational models relevant to applications spanning a variety of sectors, from automotive to biotribology and nanotechnology. Significant effort is still required to account for complementary nonlinear effects of plasticity, adhesion, friction, wear, lubrication and surface chemistry in tribological models. For each topic, we propose some research directions. © 2018 Elsevier Ltd

Ciavarella, M., Carbone, G., Vinogradov, V.
A critical assessment of kassapoglou's statistical model for composites fatigue
(2018) Facta Universitatis, Series: Mechanical Engineering, 16 (2), pp. 115-126. Cited 8 times.
https://www.scopus.com/inward/record.uri?eid=2-s2.0-85051243734&doi=10.22190%2fFUME180321014C&partnerID=40&md5=f6abd5189194ad73b778646d56261073

DOI: 10.22190/FUME180321014C
ABSTRACT: Kassapoglou has recently proposed a model for fatigue of composite materials which seems to suggest that the fatigue SN curve can be fully predicted on the basis of the statistical distribution of static strengths. The original abstract writes expressions for the cycles to failure as a function of R ratio are derived. These expressions do not require any curve fitting and do not involve any experimentally determined parameters. The fatigue predictions do not require any fatigue tests for calibration". These surprisingly ambitious claims and attractive results deserve careful scrutiny. We contend that the result, which originates from the reliability theory where exponential distributions is sometimes used to model distribution of failures when age (or wearout) has no

influence on the probability of failure, does not conform to a fatigue testing with the resulting SN curve distribution. Despite Kassapoglou's attempt to use a wearout law which seems to confirm this result even with wearout, we contend that a proper statistical treatment of the fatigue process should not make wear-out constants disappear, and hence the SN curves would depend on them, and not just on scatter of static data. These concerns explain the large discrepancies found by 3 independent studies which have tried to apply Kassapoglou's model to composite fatigue data. © 2018 by University of Niš, Serbia.

Ciavarella, M.
A JKR solution for a ball-in-socket contact geometry as a bi-stable adhesive system
(2018) Acta Mechanica, 229 (7), pp. 2835-2842.
https://www.scopus.com/inward/record.uri?eid=2-s2.0-85044201207&doi=10.1007%2fs00707-018-2138-y&partnerID=40&md5=750f9c23c59c31c5c951d367a02e9e0f

DOI: 10.1007/s00707-018-2138-y
ABSTRACT: In the present note, we start by observing that in the classical JKR theory of adhesion, using the usual Hertzian approximations, the pull-off load grows unbounded when the clearance goes to zero in a conformal “ball-in-socket” geometry. To consider the case of the conforming geometry, we use a recent rigorous general extension of the original JKR energetic derivation, which requires only adhesionless solutions, and an approximate adhesionless solution given in the literature. We find that depending on a single governing parameter of the problem, $\theta = \Delta R / (2\pi w R / E^*)$ where E^* is the plane strain elastic modulus of the material couple, w the surface energy, ΔR the clearance and R the radius of the sphere, the system shows the classical bi-stable behaviour for a single sinusoid or a dimpled surface: pull-off is approximately that of the JKR theory for θ> 0.82 only if the system is not “pushed” strong enough, otherwise a “strong adhesion” regime is found. Below this value, θ< 0.82 , a strong spontaneous adhesion regime is found similar to “full contact”. From the strong regime, pull-off will require a separate investigation depending on the actual system at hand. © 2018, Springer-Verlag GmbH Austria, part of Springer Nature.

Bertocchi, E., Mantovani, S., Ciavarella, M.
A simple method of analysis of partial slip in shrink-fitted shafts under torsion
(2018) International Journal of Mechanical Sciences, 142-143, pp. 541-546. Cited 2 times.
https://www.scopus.com/inward/record.uri?eid=2-s2.0-85047256521&doi=10.1016%2fj.ijmecsci.2018.05.027&partnerID=40&md5=aa3381171b19401b02f90ef4b1726173

DOI: 10.1016/j.ijmecsci.2018.05.027
ABSTRACT: A solution method is proposed for the partial slip problem of a shrink-fitted shaft under torsion, that relies on the superposition of axisymmetric, elastically uncoupled problems all solved with FE. First, a problem is solved for the contact pressure induced by the interference coupling alone. In the presence of remotely applied torque, antiplane slip occurs at the indenting edge contact extremity; shear actions at the slip portion of the contact interface may merely be derived by scaling the pressure profile through the friction coefficient. A semi-inverse solution approach is derived, based on the assumed extent for the near-edge slip zone; two linear elastic solutions are parametrically mated to cancel stress singularities at the stick-slip transition point, the first solution concerning the remote torque alone, and the second one addressing the interface slip actions alone. We finally discuss the results for a selection of geometrical ratios, and the viability of simplified approaches based on beam theory. © 2018 Elsevier Ltd

Ciavarella, M., D'antuono, P., Papangelo, A.
On the connection between Palmgren-Miner rule and crack propagation laws

(2018) Fatigue and Fracture of Engineering Materials and Structures, 41 (7), pp. 1469-1475. Cited 11 times.
https://www.scopus.com/inward/record.uri?eid=2-s2.0-85041464444&doi=10.1111%2fffe.12789&partnerID=40&md5=da05c83adabdae3428b8bb377369279d

DOI: 10.1111/ffe.12789
ABSTRACT: The classical Palmgren-Miner (PM) rule, despite clearly approximation, is commonly applied for the case of variable amplitude loading, and to date, there is no simple alternative. In the literature, previous authors have commented that the PM hypothesis is based on an exponential fatigue crack growth law, ie, when da/dN is proportional to the crack size a, the case that includes also Paris law for m=2, in particular. This is because they applied it by updating the damage estimate during the crack growth. It is here shown that applying PM to the "initial" and nominal (Stress vs Number of cycles) curve of a cracked structure results exactly in the integration of the simple Paris power law equation and more in general to any crack law in the form da/dN=HΔσhan. This leads to an interesting new interpretation of PM rule. Indeed, the fact that PM rule is often considered to be quite inaccurate pertains more to the general case when propagation cannot be simplified to this form (like when there are distinct initiation and propagation phases), rather than in long crack propagation. Indeed, results from well-known round-robin experiments under spectrum loading confirm that even using modified Paris laws for crack propagation, the results of the "noninteraction" models, neglecting retardation and other crack closure or plasticity effects due to overloads, are quite satisfactory, and these correspond indeed very closely to applying PM, at least when geometrical factors can be neglected. The use of generalized exponential crack growth, even in the context of spectrum loading, seems to imply the PM rule applies. Therefore, this seems closely related to the so-called lead crack fatigue lifing framework. The connection means however that the same sort of accuracy is expected from PM rule and from assuming exponential crack growth for the entire lifetime. © 2018 Wiley Publishing Ltd.

Ciavarella, M.
An approximate JKR solution for a general contact, including rough contacts
(2018) Journal of the Mechanics and Physics of Solids, 114, pp. 209-218. Cited 5 times.
https://www.scopus.com/inward/record.uri?eid=2-s2.0-85043362025&doi=10.1016%2fj.jmps.2018.03.005&partnerID=40&md5=4ff374348e56c9cc5dab1541f876bc6a

DOI: 10.1016/j.jmps.2018.03.005
ABSTRACT: In the present note, we suggest a simple closed form approximate solution to the adhesive contact problem under the so-called JKR regime. The derivation is based on generalizing the original JKR energetic derivation assuming calculation of the strain energy in adhesiveless contact, and unloading at constant contact area. The underlying assumption is that the contact area distributions are the same as under adhesiveless conditions (for an appropriately increased normal load), so that in general the stress intensity factors will not be exactly equal at all contact edges. The solution is simply that the indentation is δ=δ1−2wA'/P" where w is surface energy, δ1 is the adhesiveless indentation, A' is the first derivative of contact area and P" the second derivative of the load with respect to δ1. The solution only requires macroscopic quantities, and not very elaborate local distributions, and is exact in many configurations like axisymmetric contacts, but also sinusoidal waves contact and correctly predicts some features of an ideal asperity model used as a test case and not as a real description of a rough contact problem. The solution permits therefore an estimate of the full solution for elastic rough solids with Gaussian multiple scales of roughness, which so far was lacking, using known adhesiveless simple results. The result turns out to depend only on rms amplitude and slopes of the surface, and as in the fractal limit, slopes would grow without limit, tends to the adhesiveless result – although in this limit the JKR model is inappropriate. The solution would also go to adhesiveless result for large rms amplitude of roughness hrms, irrespective of the small scale details, and in agreement with common sense, well known experiments and previous models by the author.

Ciavarella, M.
Discussion on “Effect of out-of-phase loading on fretting fatigue response of Al7075-T6 under cyclic normal loading using a new testing apparatus” by F. Abbasi and G.H. Majzoobi
(2018) Engineering Fracture Mechanics, 192, pp. 205-209. Cited 1 time.
https://www.scopus.com/inward/record.uri?eid=2-s2.0-85041576840&doi=10.1016%2fj.engfracmech.2018.01.031&partnerID=40&md5=214ade50c34fc06d100da14286a85a4c

DOI: 10.1016/j.engfracmech.2018.01.031
ABSTRACT: Fretting fatigue has been studied mainly with constant normal load. Abbasi and Majzoobi (2017) suggest an new testing method where contact pressure can be independently varied during the test. The authors compare the case of constant normal load, with that of in phase or 90° and 180° degrees out-of-phase loads, but at the same frequency. However, the results are not obvious to interpret, and it is hoped that a reply from the authors and a discussion could lead to some progress. In particular, contact mechanics (and even the authors' own numerical simulations) seem in contrast with some experiments. Also, the case of constant normal load is found to be the least damaging despite less frictional force is developed which seems to imply an oxidation phenomenon which depends on greater exposure to air, but the time of tests seems similar. If these surprising effects are confirmed, this varying normal load effect calls for some new models in fretting. Or there is something wrong in the experiments? © 2018 Elsevier Ltd

Ciavarella, M., Papangelo, A.
On notch and crack size effects in fatigue, Paris' law and implications for Wöhler curves
(2018) Frattura ed Integrita Strutturale, 12 (44), pp. 49-63. Cited 1 time.
https://www.scopus.com/inward/record.uri?eid=2-s2.0-85045752468&doi=10.3221%2fIGF-ESIS.44.05&partnerID=40&md5=05ee812ec613a99923b39acc5167194f

DOI: 10.3221/IGF-ESIS.44.05
ABSTRACT: As often done in design practice, the Wöhler curve of a specimen, in the absence of more direct information, can be crudely retrieved by interpolating with a power-law curve between static strength at a given conventional low number of cycles N0 (of the order of 10-103), and the fatigue limit at a “infinite life”, also conventional, typically N∞=2·106 or N∞=107 cycles. These assumptions introduce some uncertainty, but otherwise both the static regime and the infinite life are relatively well known. Specifically, by elaborating on recent unified treatments of notch and crack effects on infinite life, and using similar concepts to the static failure cases, an interpolation procedure is suggested for the finite life region. Considering two ratios, i.e. toughness to fatigue threshold FK=KIc/ΔKth, and static strength to endurance limit, FR=σR/Δσ0, qualitative trends are obtained for the finite life region. Paris' and Wöhler's coefficients fundamentally depend on these two ratios, which can be also defined “sensitivities” of materials to fatigue when cracked and uncracked, respectively: higher sensitivity means stringent need for design for fatigue. A generalized Wöhler coefficient, k', is found as a function of the intrinsic Wöhler coefficient k of the material and the size of the crack or notch. We find that for a notched structure, k<k'<m, as a function of size of the notch: in particular, k'=k holds for small notches, then k' decreases up to a limiting value (which depends upon Kt for mildly notched structures, or on FK and FR only for severe notch or crack). A perhaps surprising return to the original slope k is found for very large blunt notches. Finally, Paris' law should hold for a distinctly cracked structure, i.e. having a long-crack; indeed, Paris' coefficient m is coincident with the limiting value of k'lim. The scope of this note is only qualitative and aims at a discussion over unified treatments in fatigue. © 2018, Gruppo Italiano Frattura. All rights reserved.

Papangelo, A., Hoffmann, N., Grolet, A., Stender, M., Ciavarella, M.
Multiple spatially localized dynamical states in friction-excited oscillator chains

(2018) Journal of Sound and Vibration, 417, pp. 56-64. Cited 17 times.
https://www.scopus.com/inward/record.uri?eid=2-s2.0-85041533814&doi=10.1016%2fj.jsv.2017.11.056&partnerID=40&md5=f1344c2dac0912c395100bb378b3990b

DOI: 10.1016/j.jsv.2017.11.056
ABSTRACT: Friction-induced vibrations are known to affect many engineering applications. Here, we study a chain of friction-excited oscillators with nearest neighbor elastic coupling. The excitation is provided by a moving belt which moves at a certain velocity vd while friction is modelled with an exponentially decaying friction law. It is shown that in a certain range of driving velocities, multiple stable spatially localized solutions exist whose dynamical behavior (i.e. regular or irregular) depends on the number of oscillators involved in the vibration. The classical non-repeatability of friction-induced vibration problems can be interpreted in light of those multiple stable dynamical states. These states are found within a “snaking-like” bifurcation pattern. Contrary to the classical Anderson localization phenomenon, here the underlying linear system is perfectly homogeneous and localization is solely triggered by the friction nonlinearity. © 2017 Elsevier Ltd

Ciavarella, M., Papangelo, A.
On the distribution and scatter of fatigue lives obtained by integration of crack growth curves: Does initial crack size distribution matter?
(2018) Engineering Fracture Mechanics, 191, pp. 111-124. Cited 6 times.
https://www.scopus.com/inward/record.uri?eid=2-s2.0-85041468572&doi=10.1016%2fj.engfracmech.2018.01.019&partnerID=40&md5=5de050a59d0a1b406fc2724fbd68c755

DOI: 10.1016/j.engfracmech.2018.01.019
ABSTRACT: By integrating the simple deterministic Paris’ law from a distribution of initial defects, in the form of a Frechet extreme value distribution, it was known that a distribution of Weibull distribution of fatigue lives follows exactly. However, it had escaped previous researchers that the shape parameter of this distribution tends to very high values (meaning the scatter is extremely reduced) when Paris’ exponent m approaches 2, leading to the exponential growth of cracks with number of cycles. In view of the fact that values close to m = 2 are of great importance in materials for example used for primary aircraft structures as recognized by some certification requirements (and the so-called “lead crack” methodology), we believe this conclusion may have some immediate relevance for damage tolerance procedures, or certification methods where accurate description of scatter is required. Indeed, we extend the result also to the case when Paris’ constant C is distributed, and give also an estimate of the level of scatter expected in propagation life in the most general case when C, m are both random variate alongwith the defect size distribution, based on first transforming them to uncorrelated form C0, m, and validate this with the famous Virkler set of data. We finally discuss that from known typical values of fatigue life scatter of aeronautical alloys, it is very likely that an important contribution comes from short crack growth. © 2018 Elsevier Ltd

Ciavarella, M.
A Comment on “Meeting the Contact-Mechanics Challenge” by Muser et al. [1]
(2018) Tribology Letters, 66 (1), art. no. 37, . Cited 4 times.
https://www.scopus.com/inward/record.uri?eid=2-s2.0-85041590698&doi=10.1007%2fs11249-018-0985-2&partnerID=40&md5=00983b3ec832abcf0e1ceeabe22e3261

DOI: 10.1007/s11249-018-0985-2

Papangelo, A., Ciavarella, M.

Adhesion of surfaces with wavy roughness and a shallow depression
(2018) Mechanics of Materials, 118, pp. 11-16. Cited 9 times.
https://www.scopus.com/inward/record.uri?eid=2-s2.0-85042091298&doi=10.1016%2fj.mechmat.2017.12.005&partnerID=40&md5=c4f18688a155b2d198b154e36fa0c14f

DOI: 10.1016/j.mechmat.2017.12.005
ABSTRACT: Recently, a simple and elegant “dimple” model was introduced by McMeeking et al. (2010) to show a mechanism for a bistable adhesive system involving a surface with a shallow depression. The system shows, at least for intermediate levels of stickiness, that external pressure can switch the system into a “strong adhesive” regime of full contact, or into weak adhesion and complete pull-off, similarly to the contact of surfaces with a single scale of periodical waviness. We add to this model the effect of roughness, in the simple form of axisymmetric single scale of waviness, and we show that this induces a resistance to jumping into full contact on one hand (limiting the “strong adhesion” regime), and an enhancement of pull-off and of hysteresis starting from the partial contact state on the other (enhancing the “weak adhesion” regime). We show the system depends only on two dimensionless parameters, and becomes pressure-sensitive. The model obviously is specular to the Guduru model of rough spheres (Guduru, 2007), with which it shares the limitations of the analysis assuming a connected contact (crack) area, and serves also the purpose of showing the effect of a depression into an otherwise periodic rough contact, towards the understanding of adhesion with multiple scales of roughness. © 2017

Ciavarella, M., Papangelo, A.
A modified form of Pastewka–Robbins criterion for adhesion
(2018) Journal of Adhesion, 94 (2), pp. 155-165. Cited 15 times.
https://www.scopus.com/inward/record.uri?eid=2-s2.0-85015730641&doi=10.1080%2f00218464.2017.1292139&partnerID=40&md5=d1c9f9bbfdab7ff177c45a03741565d9

DOI: 10.1080/00218464.2017.1292139
ABSTRACT: Recent numerical investigation on self-affine Gaussian surfaces by Pastewka and Robbins (PR) has led to a criterion for “stickiness” based on when the slope of the (repulsive) area–load relationship appears to become vertical in numerical simulations at a ratio of contact area to nominal one (rather arbitrarily) fixed to 1%. Since pull-off and slope of the area–load are two faces of the same medal, a simple check of the results in terms of pull-off shows that PR have many more data which fail their criterion than the ones that satisfy it, and this is evident even in their own figures. As a small improvement, a proposal to modify the criterion to better fit their own data is put forward. However, the pull-off decay seems rather exponential so that it is unclear if their slope criterion really corresponds to a “thermodynamic” limit, and consequently their conclusion that stickiness should depend only on slopes and curvature may be an artifact of their assumption of defining a secant at 1% contact area ratio and of using truncated potentials, rather than a true important property of rough contact. Both the PR criterion and the present modified one imply that for fractal dimension $D < 2.4$, stickiness should increase with resolution, so the problem of truncation of the spectrum seems ill-defined: in fact, PR define rigid self-affine surfaces with rather smooth and well-defined slopes, and not a realistic atomic roughness as first studied by Luan and Robbins. © 2017 Taylor & Francis.

Ciavarella, M.
Fracture mechanics simple calculations to explain small reduction of the real contact area under shear
(2018) Facta Universitatis, Series: Mechanical Engineering, 16 (1), pp. 87-91. Cited 12 times.
https://www.scopus.com/inward/record.uri?eid=2-s2.0-85042080321&doi=10.22190%2fFUME180108007C&partnerID=40&md5=7ec405c507585905aa5315a6b964e4cc

DOI: 10.22190/FUME180108007C
ABSTRACT: In a very recent paper, Sahli and coauthors [12] (R. Sahli et al., 2018, “Evolution of real contact area under shear”, PNAS, 115(3), pp. 471-476) studied the contact area evolution for macroscopic smooth spheres under shear load in presence of adhesion. It was found that contact area AA reduces quadratically with respect to shear load T, i.e. A=A0 -αAT2, where A0 is the contact area with no shearing, and αA is the "area reduction parameter" found to be approximately proportional to A0-3/2 across 4 orders of magnitude of A0. In this note we focus on the smooth sphere/plane contact because we believe that the case of a rough contact requires separate investigations, and we use a known model of fracture mechanics, which contains a fitting parameter β which governs the interplay between fractures modes, in order to find very good agreement between the data and the analytical predictions, developing relatively simple equations. The interaction with modes is limited.

Ciavarella, M.
A Simplified Version of Persson's Multiscale Theory for Rubber Friction Due to Viscoelastic Losses
(2018) Journal of Tribology, 140 (1), art. no. 011403, . Cited 7 times.
https://www.scopus.com/inward/record.uri?eid=2-s2.0-85027243897&doi=10.1115%2f1.4036917&partnerID=40&md5=fe65819214da9479952dfa58bd755054

DOI: 10.1115/1.4036917
ABSTRACT: We show that the full multiscale Persson's theory for rubber friction due to viscoelastic losses can be approximated extremely closely to simpler models, like that suggested by Persson in 1998 and similarly by Popov in his 2010 book (but notice that we do not make any use of the so-called "Method of Dimensionality Reduction" (MDR)), so it is essentially a single scale model at the so-called large wavevector cutoff. The dependence on the entire spectrum of roughness is therefore only confusing, at least for range of fractal dimensions of interest D ‰ 2.2, and we confirm this with actual exact calculations and reference to recent data of Lorenz et al. Moreover, we discuss the critical assumption of the choice of the "free parameter" best fit truncation cutoff.

Ciavarella, M.
A very simple estimate of adhesion of hard solids with rough surfaces based on a bearing area model
(2018) Meccanica, 53 (1-2), pp. 241-250. Cited 15 times.
https://www.scopus.com/inward/record.uri?eid=2-s2.0-85019623839&doi=10.1007%2fs11012-017-0701-6&partnerID=40&md5=1f747ad517779a79cba4e731b50fb9d6

DOI: 10.1007/s11012-017-0701-6
ABSTRACT: In the present note, we suggest a single-line equation estimate for adhesion between elastic (hard) rough solids with Gaussian multiple scales of roughness. It starts from the new observation that the entire DMT solution for “hard” spheres (Tabor parameter tending to zero) with the Maugis law of attraction can be obtained using the Hertzian relationship load-indentation and estimating the area of attraction as the increase of the bearing area geometrical intersection when the indentation is increased by the Maugis range of attraction. The bearing area model in fact results in a simpler and even more accurate solution than DMT for intermediate Tabor parameters, although it retains one of the assumptions of DMT, that elastic deformations are not affected by attractive forces. Therefore, a solution is obtained for random rough surfaces combining Persson’s adhesiveless asymptotic simple form solution with the bearing area model, which is trivially computed for a Gaussian. A comparison with recent data from extensive numerical computations involving roughness with wavelength from nano to micrometer scale shows that the approximation is quite good for the pull-off in the simulations, and it remarks the primary importance in this regime of a single parameter, the macroscopic well-defined quantity (rms)

amplitude of roughness, and small sensitiveness to rms slopes and curvatures. © 2017, Springer Science+Business Media Dordrecht.

Ciavarella, M., Papangelo, A.
On the sensitivity of adhesion between rough surfaces to asperity height distribution
(2018) Physical Mesomechanics, 21 (1), pp. 59-66. Cited 10 times.
https://www.scopus.com/inward/record.uri?eid=2-s2.0-85043387133&doi=10.1134%2fS1029959918010083&partnerID=40&md5=e1973b583f60f4a7ea7f6cc106297f2d

DOI: 10.1134/S1029959918010083
ABSTRACT: There has been a long debate about the validity of asperity models in the contact between rough surfaces, much of it concentrated on relatively minor aspects of the solution for the special case of Gaussian random processes for roughness, like the exact value of the area–load slope or the extent of the linear regime. It is shown here that in the case of adhesion, the behavior is extremely sensitive to the shape of the height distribution. We show for example results for Weibull distributions, which has been suggested in a number of practical cases from macroscopic to nanoscopic roughness. Pull-off force is found to vary by several orders of magnitude both lower and higher than in the Gaussian case, whereas the “stickiness” criterion on the adhesion parameter changes by an order of magnitude. Additionally, in some operations like chemical-mechanical polishing, tails are almost completely removed and a sharp peak develops instead of a tail: modeling this with contact on the bounded side of the Weibull distribution, stickiness seems to occur for any level of roughness. Some qualitative comparison with recent numerical experiments is attempted. © M. Ciavarella, A. Papangelo, 2017 and Pleiades Publishing. Ltd. 2018.

Ciavarella, M., Papangelo, A.
The “sport” of rough contacts and the fractal paradox in wear laws
(2018) Facta Universitatis, Series: Mechanical Engineering, 16 (1), pp. 65-75. Cited 3 times.
https://www.scopus.com/inward/record.uri?eid=2-s2.0-85042076504&doi=10.22190%2fFUME180109011C&partnerID=40&md5=dbde1a3119f57c58a9a8a064beb72571

DOI: 10.22190/FUME180109011C
ABSTRACT: In a recent paper in Science, namely, “The Contact Sport of Rough Surfaces”, Carpick summarizes recent efforts in a “contact challenge” to predict in detail an elastic contact between the mathematically defined fractal rough surfaces under (very little) adhesion. He also suggests the next steps that are needed to “fulfill da Vinci’s dream of understanding what causes friction”. However, this is disappointing as friction has been studied since the times of Leonardo and in 500 years, no predictive model has emerged, nor any significant improvement from rough contact models. Similarly, a very large effort we have spent on the “sport” of studying rough surfaces has not made us any closer to being able to predict the coefficient of proportionality between wear loss and friction dissipation which was already observed by Reye in 1860. Recent nice simulations by Aghababaei, Warner and Molinari have confirmed the criterion for the formation of debris of a single particle, proposed in 1958 by Rabinowicz, as well as Reye’s assumption for the proportionality with frictional loss, which is very close to Archard anyway. More recent investigations under variable loads suggest that Reye’s assumption is probably much more general than Archard’s law. The attempts to obtain exact coefficients with rough surfaces models are very far from predictive, essentially because for fractals most authors fail to recognize that resolution-dependence of the contact area makes the models very ill-defined. We also suggest that in the models of wear, rough contacts should be considered “plastic” and “adhesive” and introduce a new length scale in the problem. © 2018 by University of Niš, Serbia.

Ciavarella, M., Papangelo, A.

A generalized Johnson parameter for pull-off decay in the adhesion of rough surfaces
(2018) Physical Mesomechanics, 21 (1), pp. 67-75. Cited 15 times.
https://www.scopus.com/inward/record.uri?eid=2-s2.0-85042065599&doi=10.1134%2fS1029959918010095&partnerID=40&md5=2979ac205d2025f54f65a7e04776ccf6

DOI: 10.1134/S1029959918010095
ABSTRACT: There is no simple theory at present to predict accurately the decay of pull-off in the adhesion of randomly rough surfaces. The asperity model of Fuller and Tabor has shown significant error in recent numerical investigations by Pastewka and Robbins of self-affine random roughness from micrometer to atomic scale which corresponds to low values of Tabor parameter. For sinusoidal contact, the Johnson parameter, originally introduced for the JKR regime (from Johnson–Kendall–Roberts) is the dominant parameter ruling the pull-off at intermediate Tabor values. Hence, we define a generalized Johnson parameter as the ratio between the adhesive energy to the elastic strain energy to flatten the surface in the case of multiscale roughness and find that it correlates very well with the data of Pastewka and Robbins spanning almost five orders of magnitude of reduction from theoretical strength, improving significantly with respect to other possible single parameter criteria. For the most important case in practice, that of low fractal dimensions, this suggests the product of amplitude and slope of the largest wavelength components of roughness dominate pull-off decay, and not small scales features like slopes and curvatures, as suggested by Pastewka and Robbins. © M. Ciavarella, A. Papangelo, 2017 and Pleiades Publishing, Ltd., 2018.

Ciavarella, M., Xu, Y., Jackson, R.L.
Some Closed-Form Results for Adhesive Rough Contacts Near Complete Contact on Loading and Unloading in the Johnson, Kendall, and Roberts Regime
(2018) Journal of Tribology, 140 (1), art. no. 011402, . Cited 4 times.
https://www.scopus.com/inward/record.uri?eid=2-s2.0-85026900334&doi=10.1115%2f1.4036915&partnerID=40&md5=46ece78cdd52b5343255a8e7f10dfa09

DOI: 10.1115/1.4036915
ABSTRACT: Recently, generalizing the solution of the adhesiveless random rough contact proposed by Xu, Jackson, and Marghitu (XJM model), the first author has obtained a model for adhesive contact near full contact, under the Johnson, Kendall, and Roberts (JKR) assumptions, which leads to quite strong effect of the fractal dimension. We extend here the results with closed-form equations, including both loading and unloading which were not previously discussed, showing that the conclusions are confirmed. A large effect of hysteresis is found, as was expected. The solution is therefore competitive with Persson's JKR solution, at least in the range of nearly full contact, with an enormous advantage in terms of simplicity. Two examples of real surfaces are discussed. Copyright © 2018 by ASME.

Papangelo, A., Hoffmann, N., Ciavarella, M.
Load-separation curves for the contact of self-affine rough surfaces
(2017) Scientific Reports, 7 (1), art. no. 6900, . Cited 28 times.
https://www.scopus.com/inward/record.uri?eid=2-s2.0-85026503341&doi=10.1038%2fs41598-017-07234-4&partnerID=40&md5=fdaea7dff5ca55d27429a1cdc22725f1

DOI: 10.1038/s41598-017-07234-4
ABSTRACT: There are two main approximate theories in the contact of rough solids: Greenwood-Williamson asperity theories (GW) and Persson theories. Neither of them has been fully assessed so far with respect to load-separation curves. Focusing on the most important case of low fractal dimension (Df = 2.2) with extensive numerical studies we find that: (i) Persson's theory describes well the regime of intermediate pressures/contact

area, but requires significant corrective factors: the latter depend also on upper wavevector cutoff of the roughness; hence, (ii) Persson's theory does not predict the correct functional dependence on magnification; (iii) asperity theories in the discrete version even neglecting interaction effects are more appropriate in the range of relatively large separations, also to take into consideration of the large scatter in actual realization of the surface.

Ciavarella, M., Papangelo, A.
A random process asperity model for adhesion between rough surfaces
(2017) Journal of Adhesion Science and Technology, 31 (22), pp. 2445-2467. Cited 8 times.
https://www.scopus.com/inward/record.uri?eid=2-s2.0-85016081001&doi=10.1080%2f01694243.2017.1304856&partnerID=40&md5=d2b68461331cf835058f1cf892d0c47e

DOI: 10.1080/01694243.2017.1304856
ABSTRACT: A simple asperity model using random process theory is developed in the presence of adhesion, using the Derjaguin, Muller and Toporov model for each individual asperity. A new adhesion parameter is found, which perhaps improves the previous parameter proposed by Fuller and Tabor which assumed identical asperities–the model in all his variants for the radius always gives a finite pull-off force, as in Fuller and Tabor, and contrary to the exponential asperity height distribution, where the force is either always compressive, or always tensile. It is shown that a model with spheres having a radius only dependent on height is a reasonable approximation with respect to models having also a distribution of radius curvatures–the three models differ considerably, as opposed to the adhesionless case where these details did not matter. The important surface parameters in the theory determining the pull-off force are the three moments m0, m2, m4. The asymptotic form of the model at large separation is solved in closed form. As the theoretical pull-off of aligned asperities having the same radius (the average value) increases with the square root of the Nayak bandwidth of the roughness, and as asperity models are known to describe less well the surface at large bandwidth parameters, the limit behavior at large bandwidths remains uncertain. © 2017 Informa UK Limited, trading as Taylor & Francis Group.

Ciavarella, M., Papangelo, A.
Discussion of "measuring and Understanding Contact Area at the Nanoscale: A Review" (Jacobs, T. D. B., and Ashlie Martini, A., 2017, ASME Appl. Mech. Rev., 69(6), p. 061101)
(2017) Applied Mechanics Reviews, 69 (6), art. no. 065502, . Cited 14 times.
https://www.scopus.com/inward/record.uri?eid=2-s2.0-85032938366&doi=10.1115%2f1.4038188&partnerID=40&md5=d88ea8d35bb0eeba633b30f3ef162aac

DOI: 10.1115/1.4038188
ABSTRACT: Jacobs and Martini (JM) give a nice review of direct measurement methods (in situ electron microscopy), as well as indirect methods (which are based on contact resistance, contact stiffness, lateral forces, and topography) for measurement of the contact area, mostly at nanoscale. They also discuss simulation techniques and theories from single-contact continuum mechanics, to multicontact continuum mechanics and atomistic accounting. As they recognize, even at very small scales, "multiple-contacts" case occurs, and a returning problem is that the "real contact area" is often an ill-defined, "magnification" dependent quantity. The problem remains to introduce a truncation to the fractal roughness process, what was called in the 1970s "functional filtering." The truncation can be "atomic roughness" or can be due to adhesion, or could be the resolution of the measuring instrument. Obviously, this also means that the strength (hardness) at the nanoscale is ill-defined. Of course, it is perfectly reasonable to fix the magnification and observe the dependence of contact area, and strength, on any other variable (speed, temperature, time, etc.).

Papangelo, A., Ciavarella, M., Hoffmann, N.
Subcritical bifurcation in a self-excited single-degree-of-freedom system with velocity weakening–strengthening friction law: analytical results and comparison with experiments
(2017) Nonlinear Dynamics, 90 (3), pp. 2037-2046. Cited 27 times.
https://www.scopus.com/inward/record.uri?eid=2-s2.0-85029896859&doi=10.1007%2fs11071-017-3779-4&partnerID=40&md5=d3008ad32424e765ebc061490f316290

DOI: 10.1007/s11071-017-3779-4
ABSTRACT: The dynamical behavior of a single-degree-of-freedom system that experiences friction-induced vibrations is studied with particular interest on the possibility of the so-called hard effect of a subcritical Hopf bifurcation, using a velocity weakening–strengthening friction law. The bifurcation diagram of the system is numerically evaluated using as bifurcation parameter the velocity of the belt. Analytical results are provided using standard linear stability analysis and nonlinear stability analysis to large perturbations. The former permits to identify the lowest belt velocity (vlw) at which the full sliding solution is stable, the latter allows to estimate a priori the highest belt velocity at which large amplitude stick–slip vibrations exist. Together the two boundaries [vlw, vup] define the range where two equilibrium solutions coexist, i.e., a stable full sliding solution and a stable stick–slip limit cycle. The model is used to fit recent experimental observations. © 2017, The Author(s).

Ciavarella, M., Berto, F.
A simplified extension of the Crack Analogue model for fretting fatigue with varying normal load
(2017) Theoretical and Applied Fracture Mechanics, 91, pp. 37-43. Cited 6 times.
https://www.scopus.com/inward/record.uri?eid=2-s2.0-85017111320&doi=10.1016%2fj.tafmec.2017.03.011&partnerID=40&md5=5dd0b10b3603760b994d4b54b6d537fb

DOI: 10.1016/j.tafmec.2017.03.011
ABSTRACT: The stress concentration induced by fretting is studied with a simple “Crack Analogue” model (CA), vaguely inspired by the original CA proposed by MIT 20 years ago, “improved” by the first author to take into account simply both contact loads and bulk stresses loads, and even the case of finite stress concentration in the so-called “Crack Like Notch Analogue” (CLNA) model. We suggest here a very crude extension to include the case of varying normal load, where we don't attempt to solve the contact mechanics problem rigorously, only providing an estimate of the equivalent Stress Intensity Factor from the instantaneous load and contact area. Even this results in a problem which has no equivalent in standard fatigue, since it corresponds to a “crack” that is oscillating in size at each cycle. This defines the cycles of stress in the actual material points in the fretted area, but the uncertainties in the approximations suggest that only some limit cases should be approaches this way: for example, when the peaks of tangential load are obtained at about a “mean contact area” (out-of-phase loading) then the original CLNA model could be used. © 2017

Papangelo, A., Afferrante, L., Ciavarella, M.
A note on the pull-off force for a pattern of contacts distributed over a halfspace
(2017) Meccanica, 52 (11-12), pp. 2865-2871. Cited 3 times.
https://www.scopus.com/inward/record.uri?eid=2-s2.0-85014951097&doi=10.1007%2fs11012-017-0650-0&partnerID=40&md5=3fadb23e6aa2b625b4999ba636917373

DOI: 10.1007/s11012-017-0650-0
ABSTRACT: We consider a series of flat contact spots distributed over a half-space, for which the pull-off force is proportional to the square root of the total contact area over the elastic compliance. By using an electro-mechanical analogy to compute the compliance using the well-known Greenwood–Holm equation, we show how the pull-off decays for fractal patterns of contact spots with simple scaling laws, tending to zero in a fractal limit, as

the contact area goes to zero. Moreover, a qualitative assessment is made for contact of fractal rough surfaces, and it is shown that pull-off in this case is dominated by the value of the contact area reached during the loading process, which depends on the applied load, suggesting pressure-sensitive adhesion. © 2017, Springer Science+Business Media Dordrecht.

Ciavarella, M., D'Antuono, P., Demelio, G.P.
Generalized definition of “crack-like” notches to finite life and SN curve transition from “crack-like” to “blunt notch” behavior
(2017) Engineering Fracture Mechanics, 179, pp. 154-164. Cited 5 times.
https://www.scopus.com/inward/record.uri?eid=2-s2.0-85018791631&doi=10.1016%2fj.engfracmech.2017.04.048&partnerID=40&md5=e6ba82ba763b13b71c8227f274a200f4

DOI: 10.1016/j.engfracmech.2017.04.048
ABSTRACT: We start by generalizing the concept of “crack-like” notches to finite life. We note that, according to the well established Critical Distance Method (originally proposed by Neuber and Peterson), SN curves of all notches are very close to SN curves for cracked specimen, up to a certain number of cycles $N*$, above which they tend to the SN curve of the uncracked/unnotched (plain) specimen, reduced by the stress concentration factor Kt. We suggest therefore new simple estimates for rapid assessment of the notch effect under finite life: for the “crack-like” notch, substituting the notch with a crack leads to immediate use of crack solutions in databases, whereas the knowledge of the stress ahead of a notch is also well known analytically in many cases, or can be adapted. We show one example with the SAE keyhole tests, leading to fully analytical SN curves, in much better agreement with experiment than, for example, strain-life approaches using Neuber's rule. © 2017 Elsevier Ltd

Ciavarella, M., D'Antuono, P., Demelio, G.P.
A simple finding on variable amplitude (Gassner) fatigue SN curves obtained using Miner's rule for unnotched or notched specimen
(2017) Engineering Fracture Mechanics, 176, pp. 178-185. Cited 8 times.
https://www.scopus.com/inward/record.uri?eid=2-s2.0-85015622335&doi=10.1016%2fj.engfracmech.2017.03.005&partnerID=40&md5=0b22569839a937de0d60f4037ad99659

DOI: 10.1016/j.engfracmech.2017.03.005
ABSTRACT: In this note, starting from the SN curve under Constant Amplitude (CA) for the fatigue life of the uncracked (plain) specimen, we obtain that Gassner curves for Variable Amplitude (VA) loading using the simple Palmgren-Miner's law are simply shifted CA curves. Further, using the Critical Distance Method in a very clean and powerful form proposed by Susmel and Taylor for VA loading, we find similar result for notched specimen, the spectrum loading results in the same multiplicative term for notched, cracked and unnotched specimen. Hence, the present proposal can be considered as a simple empirical unified approach for rapid assessment of the notch effect under random loading, which simplifies the recent proposal by Susmel and Taylor. To their extensive validations, we add some specific comparison with experimental data from the Literature on our further findings. © 2017 Elsevier Ltd

Ciavarella, M.
On the Significance of Asperity Models Predictions of Rough Contact with Respect to Recent Alternative Theories
(2017) Journal of Tribology, 139 (2), art. no. 021402, . Cited 4 times.
https://www.scopus.com/inward/record.uri?eid=2-s2.0-84994013952&doi=10.1115%2f1.4034245&partnerID=40&md5=810f235615271df2467871e960b8d123

DOI: 10.1115/1.4034245
ABSTRACT: Recently, it has been shown that while asperity models show correctly qualitative features of rough contact problems (linearity in area-load, negative exponential dependence of load on separation which means also linearity of stiffness with load), the exact value of the coefficients are not precise for the idealized case of Gaussian distribution of heights. This is due to the intrinsic simplifications, neglecting asperity coalescence, and interaction effects. However, the issue of Gaussianity has not been proved or experimentally verified in many cases, and here, we show that, for example, assuming a Weibull distribution of asperity heights, the area-load linear coefficient is not much affected, while the relationships load-separation and, therefore, also stiffness-load do change largely, particularly when considering bounded distributions of asperity heights. It is suggested that Gaussianity of surfaces should be further tested in the experiments, before applying the most sophisticated rough contact models based on the Gaussian assumption. Copyright © 2017 by ASME.

Papangelo, A., Ciavarella, M.
Some observations on Bar Sinai, Brener and Bouchbinder (BSBB) model for friction
(2017) Meccanica, 52 (4-5), pp. 1239-1246.
https://www.scopus.com/inward/record.uri?eid=2-s2.0-84975167065&doi=10.1007%2fs11012-016-0463-6&partnerID=40&md5=0236bcd7d389c5fd0cd56f152970c4ce

DOI: 10.1007/s11012-016-0463-6
ABSTRACT: Recently, the observation of “slow fronts” in Fineberg’s group beautiful experiments in the transition from stick to slip has motivated some interesting mesoscopic models for friction, introduced along the lines of rate-state dependent models, but with a key role played by a viscous strengthening term in the friction law. In particular two models, proposed by Bar Sinai, Brener and Bouchbinder (BSBB), are considered in this work which differ in the strengthening term: the first introduces a logarithmic strengthening, the second a linear strengthening. The models aim to show that the velocity of the slip propagating fronts can be related to the much smaller slip velocities in the friction steady state curve. With the logarithmic strengthening model the increase in the local friction coefficient remains negligible if compared with the experimental results. When a stronger-than-logarithmic strengthening friction model is considered an order of magnitude increase of friction coefficient is observed in steady state friction curves, nevertheless when the local shear/pressure ratio is related with the front velocity, the results are inconsistent with the experiments. Some closed form equations are obtained to show the main results of the BSBB models, not shown in the original papers. The results and the limitations of the present models are presented. © 2016, Springer Science+Business Media Dordrecht.

Papangelo, A., Grolet, A., Salles, L., Hoffmann, N., Ciavarella, M.
Snaking bifurcations in a self-excited oscillator chain with cyclic symmetry
(2017) Communications in Nonlinear Science and Numerical Simulation, 44, pp. 108-119. Cited 18 times.
https://www.scopus.com/inward/record.uri?eid=2-s2.0-84981332751&doi=10.1016%2fj.cnsns.2016.08.004&partnerID=40&md5=9cc2e2647373c47f067e2f330c544493

DOI: 10.1016/j.cnsns.2016.08.004
ABSTRACT: Snaking bifurcations in a chain of mechanical oscillators are studied. The individual oscillators are weakly nonlinear and subject to self-excitation and subcritical Hopf-bifurcations with some parameter ranges yielding bistability. When the oscillators are coupled to their neighbours, snaking bifurcations result, corresponding to localised vibration states. The snaking patterns do seem to be more complex than in previously studied continuous systems, comprising a plethora of isolated branches and also a large number of similar but not identical states, originating from the weak coupling of the phases of the individual oscillators. © 2016 Elsevier B.V.

Ciavarella, M.
A note on the possibility of roughness enhancement of adhesion in Persson's theory
(2017) International Journal of Mechanical Sciences, 121, pp. 119-122. Cited 2 times.
https://www.scopus.com/inward/record.uri?eid=2-s2.0-85007507343&doi=10.1016%2fj.ijmecsci.2016.12.020&partnerID=40&md5=2d72178e5eb534091ac147aa8926de57

DOI: 10.1016/j.ijmecsci.2016.12.020
ABSTRACT: In an attempt to model the observed enhancement of adhesion in some classical experiments in the 1970–1980's, Persson introduced in his theory of adhesion between rough solids an “effective adhesion energy” term which is increased due to roughness-induced area increase. In the old experiments, the adhesion enhancement was measured to be up to one order of magnitude in terms of rolling resistance (and hence adhesion hysteresis), whereas it is generally smaller (up to 30–40%) for pull-off force. Here, an estimate the area increase in those experiments shows Persson's postulate is not supported since a discrepancy of at least one order of magnitude is found. Other explanations of adhesion enhancement come from more recent studies involving special axisymmetric indenters confirmed by experimental findings with negligible area increase, or by a model with well separated gaps in a fully random surface contact. However, even these models are very limited by their assumptions, and in the most general case of adhesion of random rough surfaces a comprehensive model remains elusive, and many questions remain open, requiring a detailed understanding of loading and unloading processes, of the possible effects of range of adhesive forces, of effects of roughness anisotropy, and so on. © 2016 Elsevier Ltd

Papangelo, A., Ciavarella, M.
A Maugis-Dugdale cohesive solution for adhesion of a surface with a dimple
(2017) Journal of the Royal Society Interface, 14 (127), art. no. 20160996, . Cited 13 times.
https://www.scopus.com/inward/record.uri?eid=2-s2.0-85015170694&doi=10.1098%2frsif.2016.0996&partnerID=40&md5=8c68fe3411089a8f2f7f34f047680f61

DOI: 10.1098/rsif.2016.0996
ABSTRACT: We study the adhesion of a surface with a 'dimple' which shows a mechanism for a bi-stable adhesive system in surfaces with spaced patterns of depressions, leading to adhesion enhancement, high dissipation and hysteresis. Recent studies were limited mainly to the very short range of adhesion (the so-called JKR regime), while we generalize the study to a Maugis cohesive model. A 'generalized Tabor parameter', given by the ratio of theoretical strength to elastic modulus, multiplied by the ratio of dimple width to depth has been found. It is shown that bistability disappears for generalized Tabor parameter less than about 2. Introduction of the theoretical strength is needed to have significant results when the system has gone in full contact, unless one postulates alternative limits to full contact, such as air entrapment, contaminants or fine scale roughness. Simple equations are obtained for the pull-off and for the full contact pressure in the entire set of the two governing dimensionless parameters. A qualitative comparison with results of recent experiments with nanopatterned bioinspired dry adhesives is attempted in light of the present model.

Ciavarella, M.
On pastewka and robbins' criterion for macroscopic adhesion of rough surfaces
(2017) Journal of Tribology, 139 (3), art. no. 031404, . Cited 10 times.
https://www.scopus.com/inward/record.uri?eid=2-s2.0-85029157048&doi=10.1115%2f1.4034530&partnerID=40&md5=3fb6befe04cd4138d72190ea85336e86

DOI: 10.1115/1.4034530
ABSTRACT: Pastewka and Robbins (2014, “Contact Between Rough Surfaces and a Criterion for Macroscopic Adhesion,” Proc. Natl. Acad. Sci., 111(9), pp. 3298-3303) recently have proposed a criterion to distinguish when two surfaces will stick together or not and suggested that it shows quantitative and qualitative large conflicts with asperity theories. However, a comparison with asperity theories is not really attempted, except in pull-off data which show finite pull-off values in cases where both their own criterion and an asperity based one seem to suggest nonstickiness, and the results are in these respects inconclusive. Here, we find that their criterion corresponds very closely to an asperity model one (provided we use their very simplified form of the Derjaguin-Muller-Toporov (DMT) adhesion regime which introduces a dependence on the range of attractive forces) when bandwidth a is small, but otherwise involves a root-mean-square (RMS) amplitude of roughness reduced by a factor pa. Therefore, it implies that the stickiness of any rough surface is the same as that of the surface where practically all the wavelength components of roughness are removed except the very fine ones. Copyright © 2017 by ASME.

Ciavarella, M.
On the use of DMT approximations in adhesive contacts, with remarks on random rough contacts
(2017) Tribology International, 114, pp. 445-449. Cited 11 times.
https://www.scopus.com/inward/record.uri?eid=2-s2.0-85019036855&doi=10.1016%2fj.triboint.2017.04.046&partnerID=40&md5=1ed46b97ffbfe96e7eba0028472b1a12

DOI: 10.1016/j.triboint.2017.04.046
ABSTRACT: The contact between rough surfaces with adhesion is an extremely difficult problem, and the approximation of the DMT theory (to neglect deformations due to attractive forces), originally developed for spherical contact of very small radius, is receiving some new interest. The DMT approximation leads to extremely large overestimations of the adhesive forces in the case of spherical contact, except at pull-off. For cylindrical contact, the opposite trend is found for larger contact areas. These findings suggest some caution in solving rough contacts with DMT models, unless the Tabor parameter is really low. Further approximate models like that of Pastewka & Robbins’ may be explained to work only due to a coincidence of error cancellation in their range of parameters. © 2017 Elsevier Ltd

Ciavarella, M., Papangelo, A., Afferrante, L.
Adhesion between self-affine rough surfaces: Possible large effects in small deviations from the nominally Gaussian case
(2017) Tribology International, 109, pp. 435-440. Cited 14 times.
https://www.scopus.com/inward/record.uri?eid=2-s2.0-85009786041&doi=10.1016%2fj.triboint.2017.01.003&partnerID=40&md5=68aa5af66354d411fe03a09bab0cb569

DOI: 10.1016/j.triboint.2017.01.003
ABSTRACT: It is shown that even small deviations from the ideal Gaussian random roughness case seem to lead to dramatic increase in adhesion of rough surfaces: this could be due to a finite number of asperities, or to a finite tail in the height distribution, particularly realistic at low fractal dimensions D, which is the case of most practical interest. It is emphasized that the assumption of a perfect Gaussian heigth distribution, including infinite tails, may be a strong one when studying adhesion in rough surfaces. © 2017 Elsevier Ltd

Ciavarella, M., Greenwood, J.A., Barber, J.R.
Effect of Tabor parameter on hysteresis losses during adhesive contact
(2017) Journal of the Mechanics and Physics of Solids, 98, pp. 236-244. Cited 16 times.

https://www.scopus.com/inward/record.uri?eid=2-s2.0-84993960828&doi=10.1016%2fj.jmps.2016.10.005&partnerID=40&md5=79fdb2d253122e01b75269ac88a91b9b

DOI: 10.1016/j.jmps.2016.10.005
ABSTRACT: The Tabor parameter μ is conventionally assumed to determine the range of applicability of the classical 'JKR' solution for adhesive elastic contact of a sphere and a plane, with the variation of the contact area and approach with load, and in particular the maximum tensile force (the pull-off force) being well predicted for μ>5. Here we show that the hysteretic energy loss during a contact separation cycle is significantly overestimated by the JKR theory, even at quite large values of μ. This stems from the absence of long-range tensile forces in the JKR theory, which implies that jump into contact is delayed until the separation α=0. We develop an approximate solution based on the use of Wu's solution with van der Waals interactions for jump-in, and the JKR theory for jump out of contact, and show that for μ>5, the predicted hysteresis loss is then close to that found by direct numerical solutions using the Lennard-Jones force law. We also show how the same method can be adapted to allow for contact between bodies with finite support stiffness. © 2016 Elsevier Ltd

Ciavarella, M.
On a recent stickiness criterion using a very simple generalization of DMT theory of adhesion
(2016) Journal of Adhesion Science and Technology, 30 (24), pp. 2725-2735. Cited 8 times.
https://www.scopus.com/inward/record.uri?eid=2-s2.0-84974823855&doi=10.1080%2f01694243.2016.1198445&partnerID=40&md5=c6a603b0f1ee0b24490688ca1f18b5f5

DOI: 10.1080/01694243.2016.1198445
ABSTRACT: In the contact of rough surfaces, contact occurs on smaller and smaller scales, the well-known Tabor adhesion parameter decreases and the so-called Derjaguin–Muller–Toporov (DMT) theory is the appropriate limit. Fuller and Tabor developed 40 years ago a model based on asperities and JKR theory, and more recently the author developed an asperity theory using asperities and DMT theory in the form given by Maugis. Both lead to adhesion parameters which do not depend on the range of attractive forces, in contrast to the parameter recently suggested by Pastewka and Robbins (PNAS, 111(9), 3298–3303, 2014). As it is well known from random process theory that contact of rough surfaces can be described reasonably well by asperity summits at least for low bandwidths, the Pastewka–Robbins DMT model and stickiness criterion should correspond in the limit case of a spherical contact. We therefore consider this limit case, and show that Pastewka–Robbins DMT model introduces a dependence on range of attractive forces, or on Tabor parameter, which is not correct for the sphere, and therefore may be incorrect also in general. © 2016 Informa UK Limited, trading as Taylor & Francis Group.

Ciavarella, M.
On roughness-induced adhesion enhancement
(2016) Journal of Strain Analysis for Engineering Design, 51 (7), pp. 473-481. Cited 5 times.
https://www.scopus.com/inward/record.uri?eid=2-s2.0-84988736236&doi=10.1177%2f0309324716653003&partnerID=40&md5=b353f04c604d56425aeeaa6aafb77382

DOI: 10.1177/0309324716653003
ABSTRACT: While adhesion reduction due to roughness is not surprising, roughness induced adhesion remained a puzzle until recently. Guduru and coworkers have shown a very convincing mechanism to explain both the increase of strength and of toughness in a sphere with a concentric single scale of waviness. Kesari and coworkers later showed some very elegant convenient asymptotic expansions of Guduru's solution. This enhancement is very high and indeed, using Kesari's solution, it is here shown to depend uniquely on a Johnson parameter for adhesion of a sinusoidal contact. However, counterintuitively, it leads to unbounded enhancement

for conditions of large roughness for which the Johnson parameter is very low. Guduru postulated that this enhancement should occur after sufficiently large pressure has been applied to any spherical contact. Also, although the enhancement is limited to the Johnson, Kendall and Roberts (JKR) regime of large soft materials with high adhesion, the DMT limit for the smooth sphere is found otherwise. However, for hard materials, even the Derjaguin, Muller and Toporov (DMT) limit for the smooth solids is very hard to observe, which suggests that adhesion reduction is also not yet well understood. The limitations of the assumption of simply connected area are here further discussed, and a well-known model for hard particles in contact with rough planes due to Rumpf is used to show that, in the range where an unbounded increase is predicted, orders of magnitude reduction is instead expected for rigid solids. We suggest that Guduru's model may be close to an upper bound for adhesion of rough bodies, while the Rumpf-Rabinovich model may be close to a lower bound. © IMechE 2016.

Ciavarella, M.
An upper bound to multiscale roughness-induced adhesion enhancement
(2016) Tribology International, 102, pp. 99-102. Cited 4 times.
https://www.scopus.com/inward/record.uri?eid=2-s2.0-84971325242&doi=10.1016%2fj.triboint.2016.05.017&partnerID=40&md5=efb73eed03e5295ecb5b711625a5231f

DOI: 10.1016/j.triboint.2016.05.017
ABSTRACT: Recently Guduru and coworkers have demonstrated with neat theory and experiments that both increase of strength and of toughness are possible in the contact of a rigid sphere with concentric single scale of waviness, against a very soft material. The present note tries to answer the question of a multiscale enhancement of adhesion, considering a Weierstrass series to represent the multiscale roughness, and analytical results only are used. It is concluded that the enhancement is bounded for low fractal dimensions but it can happen, and possibly to very high values, whereas it is even unbounded for high fractal dimensions, but it is also much less likely to occur, because of separated contacts.

Ciavarella, M.
Rough contacts near full contact with a very simple asperity model
(2016) Tribology International, 93, pp. 464-469. Cited 16 times.
https://www.scopus.com/inward/record.uri?eid=2-s2.0-84944769249&doi=10.1016%2fj.triboint.2015.08.046&partnerID=40&md5=b29774c755be334ff48d7c26ff1e18a7

DOI: 10.1016/j.triboint.2015.08.046
ABSTRACT: Recently, asperity theories in contact mechanics of rough surfaces have been extended in the range near full contact by elaborating on the idea of searching a corrective solution to the tensile regions of the full contact solution. The full contact solution defines a "surface" on which asperity theory can be applied. It is here shown that a very simple prediction can be made for the non-contact area, improving the accuracy near full contact with respect to the other simple solution available, that of Persson.

Ciavarella, M.
On the effect of wear on asperity height distributions, and the corresponding effect in the mechanical response
(2016) Tribology International, 101, pp. 164-167. Cited 9 times.
https://www.scopus.com/inward/record.uri?eid=2-s2.0-84964690927&doi=10.1016%2fj.triboint.2016.04.031&partnerID=40&md5=a68aa95a5c153d09743917830f6aef34

DOI: 10.1016/j.triboint.2016.04.031
ABSTRACT: Since the time of the original Greenwood and Williamson paper, it was noticed that abrasion and wear lead to possibly bimodal distribution of asperity height distribution, with the upper tail of asperities following

from the characteristics of the process. Using a limit case solution due to Borucki for the wear of an originally Gaussian distribution, it is shown here that the tail is indeed always Gaussian, but with different equivalent parameters. Therefore, if the wear process is not complete, one obtains a bimodal distribution and both may affect the resulting contact mechanics behaviour. In this short note, we illustrate just the main features of the problem. We conclude that it is an oversimplification to consider surfaces Gaussian.

Papangelo, A., Ciavarella, M.
Optimal normal load variation in wedge-shaped Coulomb dampers
(2016) Journal of Strain Analysis for Engineering Design, 51 (4), pp. 279-285. Cited 2 times.
https://www.scopus.com/inward/record.uri?eid=2-s2.0-84973512786&doi=10.1177%2f0309324715608965&partnerID=40&md5=63b5f5393851d353b3c37259964684b2

DOI: 10.1177/0309324715608965
ABSTRACT: Wedge-shaped frictional dampers are widely used in civil, mechanical and aeronautical engineering with the purpose to limit and damp vibrations, increase component fatigue life, or resist seismic loads. The wedge shape induces normal load variations which complicates the analysis. Here, we study a model which can be considered a generalization of the Griffin model, originally devised for underplatform dampers in turbine blade attachments. The model has a mass element (the body whose vibrations are to be damped) linked to the wall by means of a spring and to a massless Coulomb damper via a "contact stiffness". In Griffin's work the normal load acting on the Coulomb damper was kept constant. We introduce cyclic amplitude of the normal load, and phase shift between tangential and normal load. It is found that the optimization curves maintain the minimum for the mean normal load expected by Griffin's model. However, a lower vibration amplitude is found for in-phase loading with respect to the constant load, over the entire frequency range. When the "contact stiffness" is higher than the structure stiffness (as it is generally expected), the maximum vibration decrement for in-phase loading is around 40%. © Institution of Mechanical Engineers.

Grimaldi, G., Papangelo, A., Ciavarella, M.
A Cattaneo-Mindlin problem for a rigid punch with tangential load applied above the interface line
(2016) Proceedings of the Institution of Mechanical Engineers, Part C: Journal of Mechanical Engineering Science, 230 (9), pp. 1410-1416. Cited 3 times.
https://www.scopus.com/inward/record.uri?eid=2-s2.0-84974604065&doi=10.1177%2f0954406215625676&partnerID=40&md5=504ea4115558dc8280944d4fab5dbfea

DOI: 10.1177/0954406215625676
ABSTRACT: We study the contact between a rigid flat punch and an elastic half-space using Coulomb friction for a normal load followed by a tangential load applied at a certain height above the interface line. The study is inspired by recent experiments by the group of Jay Fineberg in Israel. Three regimes are found in the evolution of slip at the interface depending on a dimensionless parameter $\alpha = a 2 \mu h$, the ratio between the halfwidth of the contact and the product of twice friction coefficient and height of the loading point. Normal pressure and shear tractions are plotted for each case. It is shown that the effect of height does not collapse the data, contrary to the experimental data of Fineberg's setup. However, this is not surprising given the many deviations from the ideal configuration we have studied, namely the finite thickness of the bottom block, the presence of vertical surfaces on the upper block (both not permitting the assumption of halfspace elasticity) and finally local effects due to concentrated tangential load which give rise to local and not only global induced moment. © 2015 Institution of Mechanical Engineers.

Dimaki, A.V., Dmitriev, A.I., Menga, N., Papangelo, A., Ciavarella, M., Popov, V.L.

Fast High-Resolution Simulation of the Gross Slip Wear of Axially Symmetric Contacts
(2016) Tribology Transactions, 59 (1), pp. 189-194. Cited 29 times.
https://www.scopus.com/inward/record.uri?eid=2-s2.0-84959010282&doi=10.1080%2f10402004.2015.1065529&partnerID=40&md5=1f10a48a5ea5509dd22f8cca36f33277

DOI: 10.1080/10402004.2015.1065529
ABSTRACT: In the present article, we study the development of a wear profile in an axially symmetric contact under conditions of gross slip and assumption of the Reye-Archard wear criterion. Simulations are carried out using the method of dimensionality reduction and a full finite element method (FEM) formulation. The calculation time of the proposed model is several orders lower than that of FEM-based models and allows for much higher spatial resolution. © 2016 Society of Tribologists and Lubrication Engineers.

Ciavarella, M., Afferrante, L.
Adhesion of rigid rough contacts with bounded distribution of heights
(2016) Tribology International, 100, pp. 18-23. Cited 11 times.
https://www.scopus.com/inward/record.uri?eid=2-s2.0-85027931699&doi=10.1016%2fj.triboint.2015.10.033&partnerID=40&md5=74612add65e3cc73449c9482332f5b16

DOI: 10.1016/j.triboint.2015.10.033
ABSTRACT: We develop a “Bradley” (rigid) model for a rough surface with bounded or non-bounded distribution of heights. We observe a large effect of the distribution of heights: for example, for Weibull distributions, the decay from the theoretical strength becomes an inverse power law with the roughness amplitude normalized by the adhesion interaction distance. For Gaussian surfaces which are in principle unbounded distributions, only weak dependence is found on the details of the roughness spectrum. If the truncation comes from a natural process like wear where the height distribution is squashed at a certain truncation level, the latter factor dominates. © 2015 Elsevier Ltd

Ciavarella, M.
Adhesive rough contacts near complete contact
(2015) International Journal of Mechanical Sciences, 104, pp. 104-111. Cited 19 times.
https://www.scopus.com/inward/record.uri?eid=2-s2.0-84946556444&doi=10.1016%2fj.ijmecsci.2015.10.005&partnerID=40&md5=739ada5e03d970f881755acbe6e0b1bf

DOI: 10.1016/j.ijmecsci.2015.10.005
ABSTRACT: Classical asperity theories predict, in qualitative agreement with experimental observations, that adhesion is always destroyed by roughness except if the roughness amplitude is extremely small, and the materials are particularly soft. This happens for all fractal dimensions. However, these theories are limited due to the geometrical simplification, which may be particularly strong in conditions near full contact. We therefore introduce a simple model for adhesion which aims at being rigorous near full contact, where we postulate there are only small isolated gaps between the two bodies, as an extension of the adhesive-less solution proposed recently by Xu, Jackson, and Marghitu (XJM model) (Xu et al., 2014) [1], using the JKR theory for each gap. The results confirm recent theories in that we find an important effect of the fractal dimension. For D<2.5, the case which includes the vast majority of natural surfaces, there is an expected strong effect of adhesion. Only for large fractal dimensions, D>2.5, it seems that for large enough magnifications a full fractal roughness completely destroys adhesion. These results are partly paradoxical since strong adhesion is not observed in nature except in special cases.

Papangelo, A., Ciavarella, M.
Cattaneo-Mindlin plane problem with Griffith friction
(2015) Wear, 342-343, pp. 398-407. Cited 5 times.
https://www.scopus.com/inward/record.uri?eid=2-s2.0-84945935873&doi=10.1016%2fj.wear.2015.10.005&partnerID=40&md5=f33ea756d8edcba14259cdd3bb10772e

DOI: 10.1016/j.wear.2015.10.005
ABSTRACT: The classical Cattaneo-Mindlin problem for elastic halfplanes is extended for a Griffith condition for inception of slip, and otherwise following the standard Coulomb law in the sliding zone. A general solution is found using the idea of superposing normal contact pressure distributions for arbitrary 2D geometry. In particular, the full sliding component of shear is corrected with a distribution in the stick region which is formally equivalent to a JKR solution for the normal contact problem insisting on the stick area. We show that geometry affects the apparent friction coefficient (the maximum tangential load at the inception of slip), since a sudden transition to slip occurs when the stick region reaches a critical size which corresponds to the phenomenon of pull-off in the JKR solution. Example solutions are given for Hertzian geometry, power law punches and a sinusoidal profile. © 2015 Elsevier B.V.

Ciavarella, M.
Transition from stick to slip in Hertzian contact with "griffith" friction: The Cattaneo-Mindlin problem revisited
(2015) Journal of the Mechanics and Physics of Solids, 84, pp. 313-324. Cited 10 times.
https://www.scopus.com/inward/record.uri?eid=2-s2.0-84939868297&doi=10.1016%2fj.jmps.2015.08.002&partnerID=40&md5=7b8b62741054c06f536d793d11c6dbbf

DOI: 10.1016/j.jmps.2015.08.002
ABSTRACT: Classically, the transition from stick to slip is modelled with Amonton-Coulomb law, leading to the Cattaneo-Mindlin problem, which is amenable to quite general solutions using the idea of superposing normal contact pressure distributions - in particular superposing the full sliding component of shear with a corrective distribution in the stick region. However, faults model in geophysics and recent high-speed measurements of the real contact area and the strain fields in dry (nominally flat) rough interfaces at macroscopic but laboratory scale, all suggest that the transition from 'static' to 'dynamic' friction can be described, rather than by Coulomb law, by classical fracture mechanics singular solutions of shear cracks. Here, we introduce an 'adhesive' model for friction in a Hertzian spherical contact, maintaining the Hertzian solution for the normal pressures, but where the inception of slip is given by a Griffith condition. In the slip region, the standard Coulomb law continues to hold. This leads to a very simple solution for the Cattaneo-Mindlin problem, in which the "corrective" solution in the stick area is in fact similar to the mode II equivalent of a JKR singular solution for adhesive contact. The model departs from the standard Cattaneo-Mindlin solution, showing an increased size of the stick zone relative to the contact area, and a sudden transition to slip when the stick region reaches a critical size (the equivalent of the pull-off contact size of the JKR solution). The apparent static friction coefficient before sliding can be much higher than the sliding friction coefficient and, for a given friction fracture "energy", the process results in size and normal load dependence of the apparent static friction coefficient. Some qualitative agreement with Fineberg's group experiments for friction exists, namely the stick-slip boundary quasi-static prediction may correspond to the arrest of their slip "precursors", and the rapid collapse to global sliding when the precursors arrest front has reached about half the interface may correspond to the reach of the "critical" size for the stick zone.

Afferrante, L., Ciavarella, M., Demelio, G.
Adhesive contact of the Weierstrass profile

(2015) Proceedings of the Royal Society A: Mathematical, Physical and Engineering Sciences, 471 (2182), art. no. 20150248, . Cited 23 times.
https://www.scopus.com/inward/record.uri?eid=2-s2.0-84946022722&doi=10.1098%2frspa.2015.0248&partnerID=40&md5=f4ed1188977ac8d41cf7f1f40a100ac2

DOI: 10.1098/rspa.2015.0248
ABSTRACT: The Weierstrass series was considered in Ciavarella et al. (Ciavarella et al. 2000 Proc. R. Soc. Lond. A 456, 387-405. (doi:10.1098/rspa.2000.0522)) to describe a linear contact problem between a rigid fractally rough surface and an elastic half-plane. In such cases, no applied mean pressure is sufficiently large to ensure full contact, and specifically there are not even any contact areas of finite dimension. Later, Gao &Bower (Gao &Bower 2006 Proc. R. Soc. A 462, 319-348. (doi:10.1098/rspa.2005.1563)) introduced plasticity in the Weierstrass model, but concluded that the fractal limit continued to lead to what they considered unphysical predictions of the true contact size and number of contact spots, similar to the elastic case. In this paper, we deal with the contact problem between rough surfaces in the presence of adhesion with the assumption of a Johnson, Kendall and Roberts (JKR) regime.We find that, for fractal dimension D>1.5, the presence of adhesion does not qualitatively modify the contact behaviour. However, for fractal dimension D<1.5, a regularization of the contact area can be observed at a large magnification where the contact area consists of segments of finite size. Moreover, full contact can occur at all scales for D<1.5 provided the mean contact pressure is larger than a certain value. We discuss, however, the implication of our assumption of a JKR regime.

Papangelo, A., Ciavarella, M., Barber, J.R.
Fracture mechanics implications for apparent static friction coefficient in contact problems involving slip-weakening laws
(2015) Proceedings of the Royal Society A: Mathematical, Physical and Engineering Sciences, 471 (2180), art. no. 20150271, . Cited 10 times.
https://www.scopus.com/inward/record.uri?eid=2-s2.0-84939824610&doi=10.1098%2frspa.2015.0271&partnerID=40&md5=2c78a283a75fa8ec6d8d2fc825e914d6

DOI: 10.1098/rspa.2015.0271
ABSTRACT: We consider the effect of differing coefficients of static and dynamic friction coefficients on the behaviour of contacts involving microslip. The classic solutions of Cattaneo and Mindlin are unchanged if the transition in coefficients is abrupt, but if it occurs over some small slip distance, the solution has some mathematical similarities with those governing the normal tractions in adhesive contact problems. In particular, if the transition to dynamic slip occurs over a sufficiently small area, we can identify a 'JKR' approximation, where the transition region is condensed to a line. A local singularity in shear traction is then predicted, with a stress-intensity factor that is proportional to the square root of the local contact pressure and to a certain integral of the friction coefficient-slip distance relation. We can also define an equivalent of the 'small-scale yielding' criterion, which enables us to assess when the singular solution provides a good approximation. One consequence of the results is that the static coefficient of friction determined from force measurements in experiments is significantly smaller than the value that holds at the microscale.

Menga, N., Ciavarella, M.
A Winkler solution for the axisymmetric Hertzian contact problem with wear and finite element method comparison
(2015) Journal of Strain Analysis for Engineering Design, 50 (3), pp. 156-162. Cited 13 times.
https://www.scopus.com/inward/record.uri?eid=2-s2.0-84925018762&doi=10.1177%2f0309324714567489&partnerID=40&md5=2a5d744898f57007590a98ecde6bd933

DOI: 10.1177/0309324714567489
ABSTRACT: Contact problems with wear are often modelled according to the Reye-Archard law that applies locally to the wearing parts. In the transient regime, for geometries where the contact area cannot be assumed to be constant, a simple solution is possible when using the Winkler simplifying assumption. Here, we obtain such a solution in the axisymmetric contact problem, for an initially Hertzian geometry. Also, we explore the possibility to improve the solution by assuming that the Winkler constant adapts to the changing size of the contact. The correction is relevant in intermediate regimes before the solution tends to a 'rigid' asymptotic regime, independent of the elastic modulus. Comparison with a full finite element method simulation shows that the error in either contact area or peak pressure tends to be reduced from the initial error intrinsic in the Winkler assumption; however, the improvement remains small. © IMechE 2015.

Papangelo, A., Ciavarella, M.
On the limits of quasi-static analysis for a simple Coulomb frictional oscillator in response to harmonic loads
(2015) Journal of Sound and Vibration, 339, pp. 280-289. Cited 12 times.
https://www.scopus.com/inward/record.uri?eid=2-s2.0-84920044590&doi=10.1016%2fj.jsv.2014.11.028&partnerID=40&md5=c0904aba0be9bb35cde896756d095425

DOI: 10.1016/j.jsv.2014.11.028
ABSTRACT: Due to the nonlinearity of the Coulomb friction law, even the simplest models of interfaces in contact show a very rich dynamic solution. It is often desirable, especially if the frequency of loading is only a fraction of the first natural frequency of the system, to replace a full dynamic analysis with a quasi-static one, which obviously is much simpler to obtain. In this work, we study a simple Coulomb frictional oscillator with harmonic tangential load, but with constant normal load. It is found that the quasi-static solution (which has only 2 stops) captures approximately the displacement peak as long as the forcing frequency is low enough for the dynamic solution to have 2 or, even better, more than 2 stops. Instead, the velocity peak is not correctly estimated, since the velocity becomes highly irregular due to the stick-slip stops, whose number increases without limit for zero frequency. In this sense, the classical quasi-static solution, obtaining by cancelling inertia terms in the equilibrium equations, does not coincide with the limit of the full dynamic solution at low frequencies. The difference is not eliminated by adding a small amount of viscous damping, as only with critical damping, the dynamic solution is very close to the quasi-static one. Additional discrepancies arise above a limit frequency whose value depends on the ratio of the tangential load to the limit one for sliding, and correspond to when the dynamic solution turns from 2 to 0 stop per cycle. © 2014 Elsevier Ltd.

Ciavarella, M.
On the rocking and walking flat punch: Effect of elastic dissimilarity
(2015) Tribology International, 83, pp. 130-138. Cited 1 time.
https://www.scopus.com/inward/record.uri?eid=2-s2.0-84918536160&doi=10.1016%2fj.triboint.2014.11.012&partnerID=40&md5=aaeefcd4f5176fd52f4ddeac89da022d

DOI: 10.1016/j.triboint.2014.11.012
ABSTRACT: With an appropriate combination of constant and varying loads, a punch may "walk" or "ratchet", if rigid body motion is allowed. Here, a full numerical analysis is conducted to study the effect of material dissimilarity on a simple configuration. It is found that walking starts from much lower loads than in the case of similar materials, and higher shift per cycle is predicted with the same load and rocking motion, even accounting for the change of the plane strain modulus. Both elastic shakedown or cyclic dissipation are found, and convergence in these cases is relatively slow, whereas it occurs after 2 cycles of oscillations, in the walking case.

Ciavarella, M., Menga, N.
A note on wear of elastic sliding parts with varying contact area
(2015) Journal of Mechanics of Materials and Structures, 10 (3), pp. 255-264. Cited 1 time.
https://www.scopus.com/inward/record.uri?eid=2-s2.0-84945942758&doi=10.2140%2fjomms.2015.10.255&partnerID=40&md5=c6841207bc7903cfd4da9aec5b5ee26e

DOI: 10.2140/jomms.2015.10.255
ABSTRACT: Wear of sliding parts in the transient regime depends on elastic behavior of the bulk of the materials, and in general the contact area cannot be assumed to be constant, so that the problem is nonlinear. Here we look at the simple example of the classical Hertzian geometry, obtaining a simple solution for transient to uniform pressure (which is also the "rigid" limit solution) assuming out-of-plane sliding, and the approximation of the "Winkler foundation" in plane strain. Wear is assumed to vary according to the Reye-Archard law, which applies locally and only to the wearing indenter. As a further improvement, we give a more refined solution using a Winkler constant which adapts to the changing size of the contact. © 2015 Mathematical Sciences Publishers.

Papangelo, A., Ciavarella, M.
Effect of normal load variation on the frictional behavior of a simple Coulomb frictional oscillator
(2015) Journal of Sound and Vibration, 348, pp. 282-293. Cited 10 times.
https://www.scopus.com/inward/record.uri?eid=2-s2.0-84929023356&doi=10.1016%2fj.jsv.2015.03.026&partnerID=40&md5=ed6844a6eba45aaf37c7d94bd38ce774

DOI: 10.1016/j.jsv.2015.03.026
ABSTRACT: Various authors have studied the frictional contact problem for a simple concentrated mass under periodic forcing terms. In this paper, we give some additional closed form results for this problem for both the quasi-static limit and the full dynamic regime. We find in particular the regime where normal load is high enough to obtain a bounded displacement at all frequencies, which is of particular interest for "optimal" damping: in this case, the dynamic solution involves 2 stops of finite time. Contrary to the quasi-static prediction, the effect of normal load variation can decrease the peak displacement amplitude for in-phase loading up to the 80 percent. Moreover, similar to the quasi-static prediction, it can lead to a very large increase (up to more than 200 percent) for quadrature loading. Similar pattern is found for the frictional dissipation per cycle. For in-phase loading, therefore, the vibratory motion is damped more effectively, with additional beneficial effects on joint lifetime.

Barber, J.R., Ciavarella, M.
JKR solution for an anisotropic half space
(2014) Journal of the Mechanics and Physics of Solids, 64 (1), pp. 367-376. Cited 11 times.
https://www.scopus.com/inward/record.uri?eid=2-s2.0-84893767477&doi=10.1016%2fj.jmps.2013.12.002&partnerID=40&md5=6be13d5b7c0864cf09b7d3f6e4992696

DOI: 10.1016/j.jmps.2013.12.002
ABSTRACT: In this paper, the classical JKR theory of the adhesive contact of isotropic elastic spheres is extended to consider the effect of anisotropic elasticity. The contact area will then generally be non-circular, but in many cases it can reasonably be approximated by an ellipse whose dimensions are determined by imposing the energy release rate criterion at the ends of the major and minor axes. Analytical expressions are obtained for the relations between the contact force, the normal displacement and the ellipse semi-axes. It is found that the eccentricity of the contact area decreases during tensile loading and for cases when the point load solution can be accurately described by only one Fourier term, it is almost circular at pull-off, permitting an exact closed form solution for this

case. As in the isotropic JKR solution, the pull-off force is independent of the mean elastic modulus, but we find that anisotropy increases the pull-off force and this effect can be quite significant. © 2013 Elsevier Ltd.

Ciavarella, M.
Frictional energy dissipation in Hertzian contact under biaxial tangential harmonically varying loads
(2014) Journal of Strain Analysis for Engineering Design, 49 (1), pp. 27-32. Cited 3 times.
https://www.scopus.com/inward/record.uri?eid=2-s2.0-84899428080&doi=10.1177%2f0309324713497010&partnerID=40&md5=8201d37df905e5bad46c2865bafcacb0

DOI: 10.1177/0309324713497010
ABSTRACT: If a Hertzian contact is loaded by a tangential force which varies direction in time, the classical solution due to Cattaneo and Mindlin does not hold, and a numerical solution is needed. Here, we deal with the important practical case when the force describes an ellipse in the loading space, that is, the components have harmonic variation, with the in-phase (uniaxial) case being the limiting Cattaneo-Mindlin problem. We observe convergence to a steady state within the second cycle of oscillatory loading, and we describe the dependence of frictional dissipation, important both as a source of structural damping and as an indicator of potential fretting damage, on the parameters of the problem. The results show that the dissipation depends significantly on the biaxiality ratio between the tangential load components, particularly so when their amplitude is close to the full sliding limit. We find steady-state dissipation to be higher than the corresponding Cattaneo-Mindlin case for low tangential forces (with a maximum of dissipation for a rotating load). The increase is of the order of 15% only, whereas the decrease for large tangential forces seems to be more significant. This is vaguely similar to the case recently studied when the tangential force was of constant direction, but normal and tangential loads were oscillating harmonically and out of phase: this suggests that in the general case, the dissipation may be significantly larger when all the loads are out of phase. © IMechE 2013.

Papangelo, A., Stingl, B., Hoffmann, N.P., Ciavarella, M.
A simple model for friction detachment at an interface of finite size mimicking Fineberg's experiments on uneven loading
(2014) Physical Mesomechanics, 17 (4), pp. 311-320. Cited 3 times.
https://www.scopus.com/inward/record.uri?eid=2-s2.0-84911965963&doi=10.1134%2fS1029959914040080&partnerID=40&md5=507362a49ded6244bdfc1bb86e10ed9c

DOI: 10.1134/S1029959914040080
ABSTRACT: This work presents a model and simulation results for the friction detachment of a finite sized interface, following previous results on the phenomenon by Ben-David and Fineberg, namely "experiments demonstrating that the ratio of shear to normal force needed to move contacting bodies can, instead, vary systematically with controllable changes in the external loading configuration" In particular, we extend a previous one-dimensional simulation model by Bar-Sinai with colleagues to a quasi 2D model to allow for a tilting of one of the contacting blocks While Bar-Sinai with colleagues postulate that the presence of "slow fronts" of detachment (an order of magnitude lower than the usual Rayleigh fronts as in crack propagation) is due to a strengthening term in the friction law, which is not always measured in unlubricated contacts, we find slow fronts also with a purely weakening law © 2014, Pleiades Publishing, Ltd.

Kruse, S., Stingl, B., Hieke, J., Papangelo, A., Tiedemann, M., Hoffmann, N., Ciavarella, M.
The influence of loading conditions on the static coefficient of friction: A study on brake creep groan
(2014) Conference Proceedings of the Society for Experimental Mechanics Series, 7, pp. 149-160. Cited 7 times.

https://www.scopus.com/inward/record.uri?eid=2-s2.0-84988735395&doi=10.1007%2f978-3-319-04753-9_15&partnerID=40&md5=b64454425ad2e42d788c8b883cd72a60

DOI: 10.1007/978-3-319-04753-9_15
ABSTRACT: This work focuses on the phenomenon of creep groan in brake systems as a problem leading to customer complaints (Kinkaid et al., J Sound Vib 267:105–166, 2003). It is potentially induced by a stick-slip phenomenon in the friction interface, but the dynamics are not well understood yet. This work tries to contribute to the understanding of the excitation mechanisms, the interaction of different length scales and possible measures to influence the phenomenon. It presents a dual—based on simulation and experiment—approach to investigate the phenomenon employing works of Ben-David and Fineberg (Phys Rev Lett 106, 2011) and Bar Sinai et al. (Geophys Res Lett 39, 2011). On the one side using the approach of Bar Sinai et al. (Geophys Res Lett 39, 2011) a one-dimensional simulation model is built up based on the contact state evolution of a representative brake pad and disc couple. This model is used to describe the interface dynamics while taking into account the surrounding simplified loading geometry. Parallel to this approach an experimental setup with a simplified disc brake is built up. As the simulation model allows to predict the level of the average static friction coefficient for different load cases, the simple test setup allows a validation. The experimental results show that the static friction coefficient can be systematically changed by modification of the loading geometry while one still observes the perturbing influence of uncontrolled process parameters. © The Society for Experimental Mechanics, Inc. 2014.

Fan, N., Morlock, M.M., Bishop, N.E., Huber, G., Hoffmann, N., Ciavarella, M., Chen, G.X., Hothan, A., Witt, F.
The influence of stem design on critical squeaking friction with ceramic bearings
(2013) Journal of Orthopaedic Research, 31 (10), pp. 1627-1632. Cited 11 times.
https://www.scopus.com/inward/record.uri?eid=2-s2.0-84882924729&doi=10.1002%2fjor.22413&partnerID=40&md5=aa1c668c21d6ad1954d45be083ee8372

DOI: 10.1002/jor.22413
ABSTRACT: Ceramic-on-ceramic hip joints have been reported to squeak, a phenomenon that may occur in compromised lubrication conditions. One factor related to the incidence of in vivo squeaking is the stem design. However, it has not yet been possible to relate stem design to squeaking in deteriorating lubrication conditions. The purpose of this study was to determine critical friction factors for different stem designs. A hip simulator was used to measure the friction factor of a ceramic bearing with different stem designs and gradually deteriorating lubrication represented by evaporation of a volatile fluid lubricant. The critical squeaking friction factor was measured at the onset of squeaking for each stem. Critical friction was higher for the long cobalt chrome (0.32 ± 0.02) and short titanium stems (0.39 ± 0.02) in comparison with a long titanium stem (0.29 ± 0.02). The onset of squeaking occurred at a friction factor lower than that measured for dry conditions, in which squeaking is usually investigated experimentally. The results suggest that shorter or heavier stems might limit the possibility of squeaking as lubrication deteriorates. The method developed can be used to investigate the influence of design parameters on squeaking probability. Copyright © 2013 Orthopaedic Research Society.

Stingl, B., Ciavarella, M., Hoffmann, N.
Frictional dissipation in elastically dissimilar oscillating Hertzian contacts
(2013) International Journal of Mechanical Sciences, 72, pp. 55-62. Cited 7 times.
https://www.scopus.com/inward/record.uri?eid=2-s2.0-84878596025&doi=10.1016%2fj.ijmecsci.2013.03.012&partnerID=40&md5=7aa7a40d41c03f74a35f0f2cc2e33aee

DOI: 10.1016/j.ijmecsci.2013.03.012
ABSTRACT: We consider the problem of a cyclic Hertzian indentation between elastically dissimilar materials. In the case of loading, the problem was solved by Spence in a series of seminal papers, where he proved a

relationship between the solution for a rigid square-shaped punch, to that for a power-law indenter. For example, the stick area is a constant ratio of the contact area, independently on the shape of the punch. "Unfortunately", on unloading, many of the simple properties of the self-similar loading case are lost, there is a complicated development of an external region of slip which cycles in the two directions (forward and back-slip), and an inner region which continues to slip in the forward direction of the first loading cycle. However, this inner region gradually disappears, and further cyclic loading generates a convergence to a steady state solution which involves residual "locked-in" tangential slip displacements in a permanent stick zone, provided the contact is not fully unloaded. Dissipation in the steady state therefore occurs only in the external region of slip, and we provide some results for the energy dissipation per cycle, as a function of the governing parameters: coefficient of friction, Dundurs' dissimilarity constant, normal load amplitude. We also show the likely independence of energy dissipation on initial conditions, limited to the possible scenario of overloading. It is seen that dependence of energy dissipation per cycle on load amplitude is closer to quadratic than to cubic, and this may explain some experimental findings which so far were not expected from oscillatory loading of elastically similar half-spaces.

Ciavarella, M.
A simple approximate expression for finite life fatigue behaviour in the presence of 'crack-like' or 'blunt' notches
(2012) Fatigue and Fracture of Engineering Materials and Structures, 35 (3), pp. 247-256. Cited 8 times.
https://www.scopus.com/inward/record.uri?eid=2-s2.0-84857789133&doi=10.1111%2fj.1460-2695.2011.01612.x&partnerID=40&md5=c4336616c828c9d315794cbdd6ee02fe

DOI: 10.1111/j.1460-2695.2011.01612.x
ABSTRACT: In this note, we explore the possibility of simple extensions of the heuristic El Haddad formula for finite life, as an approximate expression valid for crack-like notches, and of the 'Lukáš and Klesnil' equation for blunt notches. The key starting point is to assume, in analogy to the Basquin power-law SN curve for the fatigue life of the uncracked (plain) specimen, a power law for the 'finite life'intrinsic El Haddad crack size. The approach has similarities with what recently proposed by Susmel and Taylor as a Critical Distance Method for Medium-Cycle Fatigue regime. Reasonable agreement is found with the fatigue data of Susmel and Taylor for notches, and in particular the error seems smaller in finite life than for infinite life, where these equations are already used. In these respects, the present proposal can be considered as a simple empirical unified approach for rapid assessment of the notch effect under finite life.

Putignano, C., Ciavarella, M., Barber, J.R.
Frictional energy dissipation in contact of nominally flat rough surfaces under harmonically varying loads
(2011) Journal of the Mechanics and Physics of Solids, 59 (12), pp. 2442-2454. Cited 52 times.
https://www.scopus.com/inward/record.uri?eid=2-s2.0-80054858903&doi=10.1016%2fj.jmps.2011.09.005&partnerID=40&md5=ac26fe1f1ed39d81ac75de84c2e6821b

DOI: 10.1016/j.jmps.2011.09.005
ABSTRACT: If the nominal contact tractions at an interface are everywhere below the Coulomb friction limit throughout a cycle of oscillatory loading, the introduction of surface roughness will generally cause local microslip between the contacting asperities and hence some frictional dissipation. This dissipation is important both as a source of structural damping and as an indicator of potential fretting damage. Here we use a strategy based on the Ciavarella-Jäger superposition and a recent solution of the general problem of the contact of two half spaces under oscillatory loading to derive expressions for the dissipation per cycle which depend only on the normal incremental stiffness of the contact, the external forces and the local coefficient of friction. The results show that the dissipation depends significantly on the relative phase between the oscillations in normal and tangential load - a factor which has been largely ignored in previous investigations. In particular, for given load amplitudes, the

dissipation is significantly larger when the loads are out of phase. We also establish that for small amplitudes the dissipation varies with the cube of the load amplitude and is linearly proportional to the second derivative of the elastic compliance function for all contact geometries, including those involving surface roughness. It follows that experimental observations of less than cubic dependence on load amplitude cannot be explained by reference to roughness alone, or by any other geometric effect in the contact of half spaces.

Afferrante, L., Ciavarella, M., Sackfield, A.
Rolling cylinder on an elastic half-plane with harmonic oscillations in normal force and rotational speed. Part I: Solution of the partial slip contact problem
(2011) International Journal of Mechanical Sciences, 53 (11), pp. 989-999. Cited 5 times.
https://www.scopus.com/inward/record.uri?eid=2-s2.0-80052962206&doi=10.1016%2fj.ijmecsci.2011.08.004&partnerID=40&md5=061c11f4626a059b05f93b9bf8a20dd2

DOI: 10.1016/j.ijmecsci.2011.08.004
ABSTRACT: We study the effect of harmonic oscillations during the steady rolling of a cylinder on a plane in partial slip contact conditions in the limit of small oscillations. The solution is an extension of that given in Barber et al. [1] for infinitely large coefficient of friction. Here, the effect of varying normal load and hence contact area is investigated in detail by analyzing the first order variation of the tangential force and the corresponding relative displacements. In particular, the solution is given in terms of an explicit length scale d in the Flamant solution used as a Green function. Appropriate choice of values of d allows to treat both two-dimensional problems and three-dimensional ones having elliptical contact area sufficiently elongated in the direction of the rotation axis. Also, this analysis can be used as starting point for corrugation calculations in railway tracks, where oscillations in time of the normal forces can result in non-uniform wear and hence in amplification of the corrugation. © 2011 Elsevier Ltd.

Afferrante, L., Ciavarella, M., Dellorco, M., Demelio, G.
Rolling cylinder on an elastic half-plane with harmonic oscillations in normal force and rotational speed. Part II: Energy dissipation receptances and example calculations of corrugation in the short-pitch range
(2011) International Journal of Mechanical Sciences, 53 (11), pp. 1000-1007. Cited 5 times.
https://www.scopus.com/inward/record.uri?eid=2-s2.0-80052970242&doi=10.1016%2fj.ijmecsci.2011.08.005&partnerID=40&md5=e9d466880e6fadb1740f3da75b73ce6c

DOI: 10.1016/j.ijmecsci.2011.08.005
ABSTRACT: In this paper, starting from results of Part I (Afferrante et al. [1]), we develop a procedure to evaluate the frequency dependent receptances of the energy dissipation at the contact interface, which is the quantity of interest in corrugation studies as the most known wear laws assume the local wear proportional to the frictional dissipation. These results are applied to the calculation of the growth rate of corrugation in railway tracks with an initial sinusoidal undulation. In particular, the wheel inertia and the transient contact mechanics effects are considered using a continuum description of the rail (hence neglecting pinnedpinned resonance due to the beam bending between two successive supports) by the simplest model (the Euler beam) which we can use to describe the normal receptance of the rail. The presence of a finite partial slip zone in the contact area can significantly modify the results, partially explaining the scatter of the experimental data collected in the literature. In particular, we found that partial slip affects the predicted apparent wavelength of highest growth of corrugation, and with respect to the full stick conditions, higher tractive ratio increases significantly the growth factors and non-linearity, showing an unexpected absolute maximum of growth at intermediate velocities, and the resonance-free regime becomes increasingly not a constant frequency, spanning a range of frequency between 700 and 1500 Hz even

for a given system and set of loads. Only a full investigation involving all other resonances in the system may clarify further the correspondence with experimental values, since the corrugation enigma may be due to a combination of effects. © 2011 Elsevier Ltd.

Greenwood, J.A., Putignano, C., Ciavarella, M.
A Greenwood & Williamson theory for line contact
(2011) Wear, 270 (3-4), pp. 332-334. Cited 29 times.
https://www.scopus.com/inward/record.uri?eid=2-s2.0-78650678716&doi=10.1016%2fj.wear.2010.11.002&partnerID=40&md5=9c46836649c8689cb64136ab5f485a73

DOI: 10.1016/j.wear.2010.11.002
ABSTRACT: Analyses of rough surface contact sometimes study the two-dimensional problem to avoid some of the difficulties of three-dimensional contacts, or to reduce the size of the calculations in numerical work. But two-dimensional elastic contacts introduce their own difficulties. The mean real contact pressures will be much lower than in three dimensions, and will depend strongly on the thickness of the 'slab' used to represent the elastic half-space. © 2010 Elsevier B.V.

Ciavarella, M., Monno, F.
A comparison of multiaxial fatigue criteria as applied to rolling contact fatigue
(2010) Tribology International, 43 (11), pp. 2139-2144. Cited 24 times.
https://www.scopus.com/inward/record.uri?eid=2-s2.0-77956186203&doi=10.1016%2fj.triboint.2010.06.003&partnerID=40&md5=2298b2202cd1e042e175ef17240bcf56

DOI: 10.1016/j.triboint.2010.06.003
ABSTRACT: Under rolling contact fatigue (RCF) existing multiaxial fatigue criteria are not well validated and predict significantly different results. Results for simple typical Hertzian RCF pure rolling are shown as previously remarked by the authors, the Dang Van criterion applied to RCF gives over-optimistic fatigue limits, due to the large influence of the hydrostatic component of the stress, particularly under some conditions. It is here shown that the "simpler" Crossland criterion gives a more realistic fatigue limit of Hertzian peak pressure, and the more "elaborate" Papadopoulos criterion gives an even more conservative value, of about 33.5 times higher than the fatigue limit under pure shear. It is suggested that the multiaxial criteria per se do not give a reliable estimate of the fatigue limit, and perhaps an integration within Weibull-like theories should be attempted in the future, as well as a more "unified" approach and mix of criteria taken from gears design, rolling contact in railways, and in rolling bearings. © 2010 Elsevier Ltd.

Paggi, M., Ciavarella, M.
The coefficient of proportionality κ between real contact area and load, with new asperity models
(2010) Wear, 268 (7-8), pp. 1020-1029. Cited 74 times.
https://www.scopus.com/inward/record.uri?eid=2-s2.0-77049108649&doi=10.1016%2fj.wear.2009.12.038&partnerID=40&md5=eafd563a886d38ab867df38ae8dfd909

DOI: 10.1016/j.wear.2009.12.038
ABSTRACT: Most recent numerical works on fractal surfaces have simply compared the low load limit of the coefficient of proportionality κ of the relationship between real contact area and load. In particular, that provided by Persson's theory, and that obtained from the Bush, Gibson and Thomas (BGT-A) asperity contact theory, which is a generalized form of the Greenwood and Williamson (GW) one. The two theories differ only by a numerical constant $\kappa = \sqrt{8/\pi} \approx 1.6$ vs $\kappa = \sqrt{2\pi} \approx 2.5$, but neither of the two provide an accurate prediction, Persson's value being generally too low, and BGT-A's limit being only valid for extremely large separations. A

detailed numerical comparison using a range of generated fractal surfaces permits to compare the existing models, finding for example that bandwidth is more important than Gaussianity of the surfaces. Then, we propose two new theoretical equations generalizing GW and BGT to take into account interaction effects in an approximate way (GW-I and BGT-I, respectively), which significantly improve the accuracy of original asperity models. Further, as a practical alternative to the tribologist, we suggest a new very simple discrete form of the GW model (called GW-RI) whose accuracy is similar to BGT-I, but with much lower computational cost, comparable to analytical solutions since the latter require the evaluation of the variance of the profile slopes, σm2, with a surface defined at a given set of points. The GW-RI model additionally avoids an ambiguity over how to define numerically the variance of the profile slopes, σm2.

Afferrante, L., Ciavarella, M.
Short pitch corrugation of railway tracks with wooden or concrete sleepers: An enigma solved?
(2010) Tribology International, 43 (3), pp. 610-622. Cited 7 times.
https://www.scopus.com/inward/record.uri?eid=2-s2.0-73149085058&doi=10.1016%2fj.triboint.2009.09.010&partnerID=40&md5=d7d4192ab9177543b4fdd1807386880e

DOI: 10.1016/j.triboint.2009.09.010
ABSTRACT: British Railways (BR) in the 1970s observed an increased level of short pitch corrugation after the electrification of the West Coast main line, which involved (among other things) the change from wooden to concrete sleepers. Here, using a simple model for the two systems, we find a different sensitivity to lateral creepage, a doubled growth at the "pinned-pinned" resonance regime shifted from about 600 to about 1000 Hz, but a reduced growth in the 300-600 Hz range, where most data for both systems seem to lye. Hence, despite it would be tempting to associate the increased corrugation simply to the increased (doubled) peak of normal load, there is discrepancy in the corresponding wavelength predicted by the model. Hence, there is still an "enigma" about the reasons for the enhanced corrugations. © 2009 Elsevier Ltd. All rights reserved.

Ciavarella, M., Paggi, M., Carpinteri, A.
A generalized dimensional analysis approach to fatigue crack growth
(2009) 12th International Conference on Fracture 2009, ICF-12, 8, pp. 6337-6346.
https://www.scopus.com/inward/record.uri?eid=2-s2.0-84869848511&partnerID=40&md5=9d13776494d8e0d7293ecb4783550652

ABSTRACT: Barenblatt & Botvina have pioneered dimensional analysis arguments to show that Paris' power-law shows "incomplete similarity", and the Paris' parameters C and m are not true material constants. We generalize the approach to explore the functional dependencies of m and C on more dimensionless parameters than Barenblatt & Botvina, and more experimental results, for materials including both metals and concrete. We discuss the size-scale dependencies of m and C which are quite different for the two class of materials, but explain known empirical correlations between the constants C and m.

Hoffmann, N.P., Ciavarella, M., Stolz, U., Weiß, C.
The effect of long-wavelength stiffness variation on wear pattern generation
(2009) Journal of Sound and Vibration, 322 (4-5), pp. 785-797. Cited 3 times.
https://www.scopus.com/inward/record.uri?eid=2-s2.0-63549089261&doi=10.1016%2fj.jsv.2008.11.027&partnerID=40&md5=fd89e26ce800c7d2c6f2db801d917c2a

DOI: 10.1016/j.jsv.2008.11.027
ABSTRACT: In many systems with moving contacts spatially periodic wear patterns related to structural resonances emerge. Often, however, the structural properties of the sliding system vary periodically with position.

Based on a generic minimal model the present work investigates the effect of a spatially periodic structural stiffness on wear pattern generation. Linear stability of the resulting wear dynamics is analysed using spatial Floquet analysis. It turns out that the emergence of wear patterns by instability can in general not be evaluated through stability analysis based on spatially local parameters alone. A spatially periodic stiffness can stabilize the system, depending on the wavelength and the amplitude of the spatially periodic parameter variation. The relevance of the effect is discussed and open points are addressed.

Afferrante, L., Ciavarella, M.
Short-pitch rail corrugation: A possible resonance-free regime as a step forward to explain the "enigma"?
(2009) Wear, 266 (9-10), pp. 934-944. Cited 6 times.
https://www.scopus.com/inward/record.uri?eid=2-s2.0-73149083340&doi=10.1016%2fj.wear.2008.12.003&partnerID=40&md5=177b42dee88f79c7f70f288b3164d16e

DOI: 10.1016/j.wear.2008.12.003
ABSTRACT: Rail corrugation has been noticed at least for 100 years, but (particularly short pitch one in the range 20-80mm)has been considered an enigma because measured corrugationwavelength did not relatewell withwear-instability models. The apparently large number of governing parameters has resulted in many independent efforts to generate models, which do not entirely correspond to the collected experimental evidence, and therefore there is still some uncertainty over the possible critical factors dominating the phenomenon. We showin the paper that there is a simple possiblemechanism of corrugation in longitudinal direction, apparently not noticed before in the literature by other authors, which does not necessarily correspond to a resonance in the system, not even the pinned-pinned resonance associated with the effect of discrete supports, but may depend on geometrical and loading conditions (normal load, creepage ratio, shape of the contact area, etc.), in general overall agreement with experiments. Additionally, some approximate calculations including discrete supports, using a typical concrete sleepers vertical receptance of BR use, show no evidence of corrugation mechanism at the pinned-pinned resonance, at least in the longitudinal direction. A full comparison between lateral and longitudinal mechanisms would depend on the particular value of the lateral creepage vs. longitudinal creepage, system-specific. The present "resonance-free" mechanism is a possible alternative for the data which fall outside the pinned-pinned resonance range.

Afferrante, L., Ciavarella, M.
Corrugation models and the roaring rails enigma: A simple analytical contact mechanics model based on a perturbation of carter's solution
(2009) Journal of Mechanics of Materials and Structures, 4 (2), pp. 191-209. Cited 7 times.
https://www.scopus.com/inward/record.uri?eid=2-s2.0-70350378132&doi=10.2140%2fjomms.2009.4.191&partnerID=40&md5=2fe1c13beb6db39b2a6d72c9990e1f11

DOI: 10.2140/jomms.2009.4.191
ABSTRACT: Corrugation in railways, and especially short pitch corrugation (30-80 mm), is still considered something of an enigma, despite extensive research. Models based on repeated impacts or differential wear, such as Grassie and Johnson's (1985) and Bhaskar et al.'s (1997), seem not to be conclusive, or not to suggest the correct wavelength. Further models have been suggested, either linear (Frederick, Valdivia, Hempelmann, Vassilly and Vincent) or nonlinear (Mueller), but most suggest a constant frequency mechanism invariably connected to vertical resonances of the system either in the low frequency range (50-100 Hz, the resonance of the vehicle's unsprung mass on the track stiffness referred to here as the " P2 resonance" , close to the Hertz contact resonance), or at about 1000 Hz (pinned-pinned resonance, in which the rail vibrates almost as if it were a beam pinned at sleepers), or even higher frequencies still (1700-1800 Hz). The experimental data available, by contrast, do not fit these frequency ranges. The discrepancy is tentatively explained with "contact filtering" and varied traffic

ideas, but do not convince completely. In this paper, we stress the importance of wheel inertia in coupling the oscillations of normal load, with the variations of tangential load and longitudinal creepage. A simple zeroth order perturbation of the classical rolling contact solutions is suggested, which obtains good qualitative agreement with experimental evidence. The model also leads to the recognition that vertical resonances are not crucial in explaining corrugation, as believed in previous models, since we use an extremely simple model of an Euler beam with no elastic support, having no resonances. Important factors for the growth of corrugation are the friction coefficient and the tractive ratio. High longitudinal creepage is needed to promote rapid development, and this can arise from curving, hunting motion or misaligned axles, and is probably exacerbated by high contact conformity, since this increases the fluctuating component of longitudinal creepage due to the movement of the contact point. With discrete supports, we expect a modulation of corrugation wavelength and amplitude, but this requires a separate investigation, not just the inclusion of pinned-pinned resonance.

Ciavarella, M., Paggi, M., Carpinteri, A.
One, no one, and one hundred thousand crack propagation laws: A generalized Barenblatt and Botvina dimensional analysis approach to fatigue crack growth
(2008) Journal of the Mechanics and Physics of Solids, 56 (12), pp. 3416-3432. Cited 57 times.
https://www.scopus.com/inward/record.uri?eid=2-s2.0-55749110899&doi=10.1016%2fj.jmps.2008.09.002&partnerID=40&md5=338624ab2feb2beac6652def71977dfc

DOI: 10.1016/j.jmps.2008.09.002
ABSTRACT: Barenblatt and Botvina with elegant dimensional analysis arguments have elucidated that Paris' power-law is a weak form of scaling, so that the Paris' parameters C and m should not be taken as material constants. On the contrary, they are expected to depend on all the dimensionless parameters of the problem, and are really "constants" only within some specific ranges of all these. In the present paper, the dimensional analysis approach by Barenblatt and Botvina is generalized to explore the functional dependencies of m and C on more dimensionless parameters than the original Barenblatt and Botvina, and experimental results are interpreted for a wider range of materials including both metals and concrete. In particular, we find that the size-scale dependencies of m and C and the resulting correlation between C and m are quite different for metals and for quasi-brittle materials, as it is already suggested from the fact the fatigue crack propagation processes lead to m = 2 - 5 in metals and m = 10 - 50 in quasi-brittle materials. Therefore, according to the concepts of complete and incomplete self-similarities, the experimentally observed breakdowns of the classical Paris' law are discussed and interpreted within a unified theoretical framework. Finally, we show that most attempts to address the deviations from the Paris' law or the empirical correlations between the constants can be explained with this approach. We also suggest that "incomplete similarity" corresponds to the difficulties encountered so far by the "damage tolerant" approach which, after nearly 50 years since the introduction of Paris' law, is still not a reliable calculation of damage, as Paris himself admits in a recent review.

Ciavarella, M., Greenwood, J.A., Paggi, M.
Inclusion of "interaction" in the Greenwood and Williamson contact theory
(2008) Wear, 265 (5-6), pp. 729-734. Cited 137 times.
https://www.scopus.com/inward/record.uri?eid=2-s2.0-43549107244&doi=10.1016%2fj.wear.2008.01.019&partnerID=40&md5=3809c42eb735bb255b6e0e86fef0192a

DOI: 10.1016/j.wear.2008.01.019
ABSTRACT: Recent direct implementation of asperity theories is reinterpreted here to formulate an improved version of the Greenwood and Williamson (GW) theory with the inclusion of interaction between asperities. This is achieved by treating the contact pressures as uniformly distributed over the apparent contact area and the resulting deformation as uniform. The correction is equivalent to an increase of the effective separation of the

mean planes by a quantity proportional to the nominal pressure, resulting in a reduction of the "real" area of contact and of total load for a given separation. However, the area-load relationship is unchanged. The correction effectively depends on the ratio between the nominal pressure and the elastic modulus multiplied by the ratio between the size of the nominal contact area and standard deviation of the asperity heights. For contacts much larger than the size of roughness, uniform interaction effects would be dominant at relatively modest pressures (particularly for soft materials). This also means that the effect of interaction is unlimited. However, the only significant change is in the prediction of gas-tightness, it is harder to seal a large area than a small one. The modification of the theory has a significant effect on stiffness and conductance. Indeed, a parallel is drawn between this correction and the "clustering" terms of resistance in the Holm-Greenwood formulae for a cluster of circular spots. Finally, numerical contact simulations using Weierstrass-Mandelbrot (WM) surfaces show a general agreement with the improved theory but also significant scatter for low load levels. Taking into account the effect of asperity interaction, the improved GW theory is now able to predict the numerically obtained contact response for intermediate load levels. © 2008.

Afferrante, L., Ciavarella, M.
Thermo-elastic dynamic instability (TEDI) - A review of recent results
(2008) Journal of Engineering Mathematics, 61 (2-4), pp. 285-300. Cited 12 times.
https://www.scopus.com/inward/record.uri?eid=2-s2.0-47349084585&doi=10.1007%2fs10665-007-9184-0&partnerID=40&md5=6d442bd5327dec9d1924d029b78572a8

DOI: 10.1007/s10665-007-9184-0
ABSTRACT: Frictional instabilities arise in a number of engineering and scientific contexts, when the presence of friction renders unstable the uniform motion between parts under nominally uniform conditions. Various classes of friction instabilities exist, those involving friction weakening with speed, and those at constant coefficient of friction. In the latter class, in turn, there are Dynamic Instabilities (DI) and Thermo-Elastic Instabilities (TEI). Recently, by including inertia terms in the formulations of the simple models already studied, the merging of TEI and DI has shown that, although the coupling of dynamic and thermal terms is generally weak (given the significant difference in the typical time scales of the two processes), thermal effects are capable of making otherwise neutrally stable dynamic modes unstable, rendering the new form of instability TEDI (ThermoElastoDynamic Instability) potentially interesting in a number of applications. Some results involving 1D and 2D models of TEDI are reviewed. © Springer Science + Business Media B.V. 2007.

Barber, J.R., Klarbring, A., Ciavarella, M.
Shakedown in frictional contact problems
(2008) 2007 Proceedings of the ASME/STLE International Joint Tribology Conference, IJTC 2007, PART A, pp. 517-519.
https://www.scopus.com/inward/record.uri?eid=2-s2.0-43349106624&doi=10.1115%2fIJTC2007-44040&partnerID=40&md5=642fd482cad7060ff4f4f188df363462

DOI: 10.1115/IJTC2007-44040
ABSTRACT: If a linear elastic system with frictional interfaces is subjected to periodic loading, any slip which occurs generally reduces the tendency to slip during subsequent cycles and in some circumstances the system 'shakes down ' to a state without slip. It has often been conjectured that a frictional Melan's theorem should apply to this problem - i.e. that the existence of a state of residual stress sufficient to prevent further slip is a sufficient condition for the system to shake down. Here we discuss recent proofs that this is indeed the case for 'complete' contact problems if there is no coupling between relative tangential displacements at the interface and the corresponding normal contact tractions. By contrast, when coupling is present, the theorem applies only for a few

special two-dimensional discrete cases. Counter-examples can be generated for all other cases. These results apply both in the discrete and the continuum formulation.

Ciavarella, M., Barber, J.
Influence of longitudinal creepage and wheel inertia on short-pitch corrugation: A resonance-free mechanism to explain the roaring rail phenomenon
(2008) Proceedings of the Institution of Mechanical Engineers, Part J: Journal of Engineering Tribology, 222 (3), pp. 171-181. Cited 15 times.
https://www.scopus.com/inward/record.uri?eid=2-s2.0-44949106358&doi=10.1243%2f13506501JET373&partnerID=40&md5=1769be8e4daa39dd3031eb53af5eb843

DOI: 10.1243/13506501JET373
ABSTRACT: Short-pitch corrugation (30-80 mm in wavelength) in railways, despite being well known since the early days of the railways because of its criticality in producing damage, 'roaring rail' or 'howling wheel' noise, and indirectly rolling contact fatigue, is considered an enigmatic phenomenon. In fact, most available data seem to show a non-linearly increasing wavelength with speed, and an almost fixed wavelength, while most models based on system resonances predict a fixed frequency. More enigmatic still, many data points fall in a range of frequencies where there is no evident resonance in the wheel-railtrack system (the large gap between the low frequencies resonances, from 50 to 300 Hz and the very high pinned-pinned mode resonant frequencies which correspond generally to 850-1100 Hz in railways. Yet the most common classifications of corrugation continue to associate corrugation to frequency-fixing mechanisms. Johnson's early studies on the Hertz normal spring resonance suggest that plasticity-based repeats impact mechanism, or differential wear mechanism both seemed to be not appropriate to explain short-pitch corrugation. In particular, longitudinal creepage (obviously associated with braking or acceleration very common on uphill grades, near stations, but also in curves where profiles provide insufficient steering capability) seemed to act to suppress corrugation, rather than promoting it, as suggested in the model of Grassie and Johnson. Only a few, very comprehensive models that include all the relevant receptances consider the effect of wheel inertia: indeed, these models indicate many possible corrugation regimes and, in particular, point at lateral creepage mechanisms at the pinned-pinned resonant frequency as giving much larger growth than longitudinal creepage, so the possibility of a corrugation regime independent of wheelset or railtrack resonances has largely remained hidden, despite it being present in some results. In this paper, a simple model that returns to a pure longitudinal creepage mechanism is suggested, showing that it is essential to include the rotational dynamics of the wheel in the system, similar to Grassie and Johnson's model. In particular, a simple full-stick Winkler-contact mechanics model can estimate the effect of transient contact mechanics. For typical inertias, the conditions are closer to the constant tangential load (which is the correct limit at zero speed anyway) and seem to explain the basic features of wear-induced instability in the existing experimental data. For larger inertias, which may also be possible for heavy wheelsets, the model predicts results closer to Grassie and Johnsores assumption of constant creepage, i.e. only a limited range of possible short-pitch corrugation. The model also suggests that although the growth of corrugation depends strongly on the amplification of the normal load, the wavelength of this mode of corrugation depends very little on the vertical resonances of the systems, so that it would persist even in a model with no resonance altogether. It is possible that the exact frequency of this regime depends on the details of the contact geometry, here simplified using the Winkler model. Finally, a reason why this mechanism of longitudinal creepage corrugation, despite perhaps giving 10-20 times apparently lower growth than lateral creepage, may indeed be the correct mechanism to interpret the classical data, is that longitudinal creepage can he 10 times higher than lateral (5 per cent instead of 0.5 per cent), and as corrugation growth is proportional to square of creepage, there is a factor 100 that largely compensates for this. There is still some progress to be made to obtain a reliable model to compare the various regimes, but clearly this regime should be considered when devising remedies to corrugation. © IMechE 2008.

Ciavarella, M., Dibello, S., Demelio, G.
Conductance of rough random profiles
(2008) International Journal of Solids and Structures, 45 (3-4), pp. 879-893. Cited 26 times.
https://www.scopus.com/inward/record.uri?eid=2-s2.0-36049030704&doi=10.1016%2fj.ijsolstr.2007.09.009&partnerID=40&md5=490af9c3d79125dfa9a341704a3ac155

DOI: 10.1016/j.ijsolstr.2007.09.009
ABSTRACT: Recently, the real contact area and the compliance and electrical resistance for a rough surface defined with a Weierstrass series have been studied under the assumption that superposed self-affine sine waves had well separated wavelengths, extending the celebrated procedures pioneered by Archard [Archard, J.F., 1957. Elastic deformation and the laws of friction. Proc. R. Soc. Lond. A 243, 190-205]. Here, more realistic fractal rough surface profiles are considered, by using the Weierstrass series with random phases, and with much lower separation of the various scales, using a full or a hybrid numerical/analytical technique. A non-linear layer algorithm is developed which is a very efficient approximate tool to study this problem, avoiding the need for averaging over various realizations of profiles with random phases. The multiscale problem is solved by a cascade of 2-scales problems, each of which is solved with a few elements for an imposed contact area, deriving load as a function of indentation and the conductance by differentiation using Barber's analogy theorem. Dimensionless results for the conductance as a function of applied pressures show that the conductance seems to be close to a power law at low loads, and is nearly linear at intermediate loads (following the normalized single sinusoidal case except at the origin). At high loads, the conductance becomes strongly dependent on fractal dimension because of weak dependence on the contribution of small wavelength scales (higher order terms in the series). Since roughness tends to be squeezed out, the conductance tends to increase more than linearly (more so, the smaller is the fractal dimension). However, another limit could be found in terms of the finite size of the specimen, which may suggest reaching a finite limit. The resulting curves could then be sigmoidal, as confirmed by qualitative comparisons with experiments in the literature.

Barber, J.R., Klarbring, A., Ciavarella, M.
Shakedown in frictional contact problems for the continuum
(2008) Comptes Rendus - Mecanique, 336 (1-2), pp. 34-41. Cited 40 times.
https://www.scopus.com/inward/record.uri?eid=2-s2.0-38949101581&doi=10.1016%2fj.crme.2007.10.013&partnerID=40&md5=b83c4d5d63233a21100645d3f88037c3

DOI: 10.1016/j.crme.2007.10.013
ABSTRACT: Elastic systems with frictional interfaces subjected to periodic loading are often found to 'shake down' in the sense that frictional slip ceases after the first few loading cycles. The similarities in behaviour between such systems and monolithic bodies with elastic-plastic constitutive behaviour have prompted various authors to speculate that Melan's theorem might apply to them-i.e. that the existence of a state of residual stress sufficient to prevent further slip is a sufficient condition for the system to shake down. In this article, we prove this result for 'complete' contact problems in the continuum formulation for systems with no coupling between relative tangential displacements at the interface and the corresponding normal contact tractions. This condition is satisfied for the contact of two half spaces, or of a rigid body with a half space if Dundurs' constant $\beta = 0$. It is also satisfied for the contact of two symmetric bodies of similar materials at the plane of symmetry. To cite this article: J.R. Barber et al., C. R. Mecanique 336 (2008).

Barber, J.R., Ciavarella, M., Afferrante, L., Sackfield, A.
Effect of small harmonic oscillations during the steady rolling of a cylinder on a plane
(2008) International Journal of Mechanical Sciences, 50 (9), pp. 1344-1353. Cited 10 times.

https://www.scopus.com/inward/record.uri?eid=2-s2.0-55349111794&doi=10.1016%2fj.ijmecsci.2008.07.011&partnerID=40&md5=bfeba3ee0c895ed5f7797f00823f6ae1

DOI: 10.1016/j.ijmecsci.2008.07.011
ABSTRACT: If a wheel rolling over a rail transmits a tangential traction, frictional microslip occurs in part of the contact area, resulting in energy dissipation and localized wear. If the applied forces oscillate in time, the resulting wear will be non-uniform, resulting in 'corrugations' that can grow with progressive passes, depending on the dynamics of the overall system. In this paper, a linear perturbation method is used to obtain closed-form expressions for the receptance of a two-dimensional rolling contact subjected to small oscillations in normal force and rotational speed superposed on a mean value in the limit of large coefficient of friction. Corresponding expressions are also obtained for the amplitude and phase of the energy dissipation in the contact, which is expected to correlate with the local wear rate. The results are compared with a simpler Winkler model of the contact and with other models that have been used for the analysis of rail corrugation. Surprisingly good agreement is obtained with numerical results due to Gross-Thebing for the receptances due to oscillations in rotational speed.

Klarbring, A., Ciavarella, M., Barber, J.R.
Shakedown in elastic contact problems with Coulomb friction
(2007) International Journal of Solids and Structures, 44 (25-26), pp. 8355-8365. Cited 60 times.
https://www.scopus.com/inward/record.uri?eid=2-s2.0-35448974955&doi=10.1016%2fj.ijsolstr.2007.06.013&partnerID=40&md5=fc97301d839ab3b29fa3fe865e760876

DOI: 10.1016/j.ijsolstr.2007.06.013
ABSTRACT: Elastic systems with frictional interfaces subjected to periodic loading are sometimes predicted to 'shake down' in the sense that frictional slip ceases after the first few loading cycles. The similarities in behaviour between such systems and monolithic bodies with elastic-plastic constitutive behaviour have prompted various authors to speculate that Melan's theorem might apply to them - i.e., that the existence of a state of residual stress sufficient to prevent further slip is a sufficient condition for the system to shake down. In this paper, we prove this result for 'complete' contact problems in the discrete formulation (i) for systems with no coupling between relative tangential displacements at the interface and the corresponding normal contact tractions and (ii) for certain two-dimensional problems in which the friction coefficient at each node is less than a certain critical value. We also present counter-examples for all systems that do not fall into these categories, thus giving a definitive statement of the conditions under which Melan's theorem can be used to predict whether such a system will shake down.

Yao, H., Ciavarella, M., Gao, H.
Adhesion maps of spheres corrected for strength limit
(2007) Journal of Colloid and Interface Science, 315 (2), pp. 786-790. Cited 27 times.
https://www.scopus.com/inward/record.uri?eid=2-s2.0-34548857351&doi=10.1016%2fj.jcis.2007.07.021&partnerID=40&md5=40763857fa67fc299ecfba04a6bfa064

DOI: 10.1016/j.jcis.2007.07.021
ABSTRACT: Present understanding of adhesion is mostly due to the well-known contact theories for spheres, including JKR (Johnson-Kendall-Roberts), DMT (Derjaguin-Muller-Toporov) and MD (Maugis-Dugdale). Since most of the models exhibit their optimal applicability only in a specific regime, an adhesion map has been developed [K.L. Johnson, J.A. Greenwood, J. Colloid Interface Sci. (1997)] to guide the selection among different models. In the JG (Johnson-Greenwood) map, however, an important physical fact has been neglected that the adhesion strength must not exceed the theoretical strength; thereby the applicability of the classical adhesion

models is overestimated and misguidance may arise from the JG map. To avoid this limitation, in this paper we introduce the strength limit into the adhesion map and find that the selection of adhesion models depends not only on the Tabor number but also on the ratio of the theoretical strength to the stiffness. Given this ratio, there exists a critical Tabor number or the size of the sphere, below which adhesion is dominated by the limiting strength and the classical adhesion models are no longer appropriate for spheres. These results eventually lead to a corrected adhesion map for spheres.

Ciavarella, M., Strozzi, A., Baldini, A., Giacopini, M.
Normalization of load and clearance effects in ball-in-socket-like replacements
(2007) Proceedings of the Institution of Mechanical Engineers, Part H: Journal of Engineering in Medicine, 221 (6), pp. 601-611. Cited 8 times.
https://www.scopus.com/inward/record.uri?eid=2-s2.0-35148889362&doi=10.1243%2f09544119JEIM200&partnerID=40&md5=813f52d114803f191ae2c53c5c88b20b

DOI: 10.1243/09544119JEIM200
ABSTRACT: A normalizing loading parameter useful in summarising the mechanical response of plane pin-in-plate-like contacts is extended to axisymmetric ball-in-socket-like contacts. An example addressing a compliant layered artificial hip joint is presented, and the usefulness of the normalizing loading parameter is evidenced. © IMechE 2007.

Afferrante, L., Ciavarella, M.
Thermoelastic Dynamic Instability (TEDI) in frictional sliding of a half-space against a rigid non-conducting wall
(2007) Journal of Applied Mechanics, Transactions ASME, 74 (5), pp. 875-884. Cited 5 times.
https://www.scopus.com/inward/record.uri?eid=2-s2.0-35348843407&doi=10.1115%2f1.2712232&partnerID=40&md5=4602a87c0d4a7d27c7b6a85c2f0f9be2

DOI: 10.1115/1.2712232
ABSTRACT: In the sliding of half-spaces with constant friction coefficient, two classes of instabilities are well known: thermoelastic instability (TEI), which occurs for sufficiently long wavelengths and Dynamic Instability (DI), which happens at sufficiently high friction coefficient, and whose growth factor increases linearly with wave number. Although the two phenomena look therefore quite distinct, their coupling is discussed here for an elastic and conducting half-space sliding against a rigid and non-conducting wall. The coupling between thermal and dynamic effects is not always negligible. In fact, surprisingly, new areas of instability are found, called thermoelastic dynamic instabilities (TEDI), similar to TEI at high speeds and DI at low speeds. TEDI lowers the critical speed and friction coefficient in many conditions even to zero. At low speeds, TEDI is ill-posed as DI at small wavelengths, and hence a regularized friction law like the Rice-Ruina one would probably be needed to correct the results. Copyright © 2007 by ASME.

Afferrante, L., Ciavarella, M.
Thermo-elastic dynamic instability (TEDI) in frictional sliding of two elastic half-spaces
(2007) Journal of the Mechanics and Physics of Solids, 55 (4), pp. 744-764. Cited 12 times.
https://www.scopus.com/inward/record.uri?eid=2-s2.0-34047243857&doi=10.1016%2fj.jmps.2006.10.004&partnerID=40&md5=147b97482cc218873eb014c8ff0a5bb8

DOI: 10.1016/j.jmps.2006.10.004
ABSTRACT: In some simplified 1D models, we recently studied the coupling of TEI (thermoelastic instability) and DI (dynamic instability), finding that thermal effects can render unstable the otherwise neutrally stable natural elastodynamic modes of the system, giving rise to a new family of instability which we called TEDI. Here, we study

the general case of two sliding elastic half-planes, finding again a relatively weak coupling between thermal and dynamic effects, and the general family of instability TEDI class is found to modify both the otherwise separated TEI and DI classes. The growth factor, the phase velocity and the migrating speeds of the perturbations are wavelength-dependent, and it is difficult to give a complete picture given the high number of materials' parameters, and the dependence on speed, friction coefficient, and the underlying uniform pressure. However, a set of results are given for "large" and "small" mismatch of shear wave speeds in the materials, and as a function of (i) friction coefficient; (ii) sliding speed V0; (iii) wavenumber parameter γ. In the case of small mismatch, generalized Rayleigh waves exists already under frictionless conditions, the critical f for instability is zero. DI dominates over TEI typically for large wavenumbers, where the growth factors increase without limit and hence become eventually meaningless, requiring regularizations for example with rate-state dependent friction laws. TEI growth factors vice versa have a maximum at a certain wavenumber and therefore are always well posed. Larger coupling effects are noticed for two materials with large mismatch, but significantly only for sliding speeds comparable with the wave speed. In general, TEI growth factors increase with speed, whereas DI growth factors increase with speed for similar materials and decrease when the mismatch between materials is large.

Afferrante, L., Ciavarella, M.
A note on thermoelastodynamic instability (TEDI) for a 1D elastic layer: Force control
(2007) International Journal of Solids and Structures, 44 (5), pp. 1380-1390. Cited 10 times.
https://www.scopus.com/inward/record.uri?eid=2-s2.0-33846035478&doi=10.1016%2fj.ijsolstr.2006.06.030&partnerID=40&md5=c34247df8953a9db3135edda7728b52c

DOI: 10.1016/j.ijsolstr.2006.06.030
ABSTRACT: Recently, a new mechanism of frictional instability has been identified, for an elastic layer sliding against a rigid non-conducting support. This mechanism emerges where neither elastodynamic instabilities (e.g. 'brake squeal') nor thermoelastic ('TEI') instabilities would be active. The time scales of these processes differ considerably, so it is usual to neglect coupling between them - yet, the natural elastodynamic vibrations of the layer become unstable at arbitrarily low sliding speeds. In this paper, the force control analogous problem is treated, for which, contrary to the previous case, a pure TEI instability does not exist. The results show similar mechanisms of instability, but now the average pressure in the limit cycle is given and hence only the shape of the cycle can change.

Ciavarella, M., Delfine, V., Demelio, G.
A "re-vitalized" Greenwood and Williamson model of elastic contact between fractal surfaces
(2006) Journal of the Mechanics and Physics of Solids, 54 (12), pp. 2569-2591. Cited 103 times.
https://www.scopus.com/inward/record.uri?eid=2-s2.0-33749591905&doi=10.1016%2fj.jmps.2006.05.006&partnerID=40&md5=fd934e833f1298add7e855db75ca109b

DOI: 10.1016/j.jmps.2006.05.006
ABSTRACT: Greenwood and Williamson in 1966 (GW) proposed a theory of elastic contact mechanics of rough surfaces which is today the foundation of many theories in tribology (friction, adhesion, thermal and electrical conductance, wear, etc.). However, the theory has periodically received criticisms for the "resolution-dependence" of the asperity features. Greenwood himself has recently concluded that: "The introduction by Greenwood and Williamson in 1966 of the definition of a 'peak' as a point higher than its neighbours on a profile sampled at a finite sampling interval was, in retrospect, a mistake, although it is possible that it was a necessary mistake" [Greenwood and Wu, 2001. Surface roughness and contact: an apology. Meccanica 36 (6), 617-630]. We propose a "discrete" version of the GW model, keeping the approximation of a surface by quadratic functions near summits, where the summit arrangement is found from numerical realizations or real surfaces scans. The contact

is then solved either summing the Hertzian relationships, or considering interaction effects to the first-order in a very efficient algorithm. We conduct experiments on Weierstrass-Mandelbrot fractal surfaces, concluding that:(1)the real contact area-load relationship is well captured by the original GW theoretical model, once the correct mean radius is used. The relationship is robust and shows relatively little scatter;(2)the conductance-load relationship is vice versa only approximately given by the original GW theoretical model. Significant deviations from linearity and significant scatter seem to be found, particularly at low fractal dimensions;(3)the load, area and conductance dependences with separation show significant dependence on the actual phase arrangements, and hence significant scatter at large separations. Effect of interaction is seen strongly at low separations, where scatter is minimal. The discrete GW model permits to include these effects, except when the asperity description breaks down. Refinements of the original GW theory using the full random process theory (such as that by Bush Gibson and Thomas, BGT) result only in small improvements with a significant additional complication. However, the BGT relationship between contact area and load at low loads is more accurate than the more recent theory by Persson. The distribution derived from the original GW theory has been obtained, and shown to be closer to the numerical results than that predicted by the Persson model, even if the area error is removed. It is concluded that the original GW theory deserves the general success received so far, since the resolution-dependence of geometrical features is an intrinsic feature of "fractals" but not a problem for the GW theory, when interaction effects are included.

Ciavarella, M., Murolo, C., Demelio, G.
On the elastic contact of rough surfaces: Numerical experiments and comparisons with recent theories
(2006) Wear, 261 (10), pp. 1102-1113. Cited 34 times.
https://www.scopus.com/inward/record.uri?eid=2-s2.0-33750510661&doi=10.1016%2fj.wear.2006.02.001&partnerID=40&md5=b62e93f7f4c29556e97b3c451ae6e352

DOI: 10.1016/j.wear.2006.02.001
ABSTRACT: Some numerical experiments are conducted for studying the decrease of the elastic contact area in the elastic contact of fractal random surfaces when adding components of roughness of progressively smaller wavelengths. In particular, Fourier and Weierstrass random series are used, and a recent accurate and efficient method developed by the authors is used, involving superpositions of overlapping triangles. Some comparisons are made using two recent theories, that of Ciavarella et al. published in 2000 on the deterministic Weierstrass fractal profile, and that of Persson published in 2001 on random generic contact. We show that both theories tend to underpredict the contact area by a significant (and similar) factor in these representative cases in the region of light loads (partial contact), where the non-linearities of the contact mechanics are not included in neither of the formulations. In Persson's theory case, the discrepancy is particularly large at high fractal dimensions of the profile, where in theory the numerical experiments should be more closely reproducing a true Gaussian process. The Ciavarella et al. "Archard-like" theory, is only accurate when the parameter γ (the ratio of successive wavelengths) is unrealistically large. However, we only tested the Ciavarella et al. theory in the simplified "Hertzian approximation" form assuming partial contact at the peaks of contact, although we don't expect the full version to improve dramatically the results.

Afferrante, L., Ciavarella, M.
"Frictionless" and "frictional" ThermoElastic Dynamic Instability (TEDI) of sliding contacts
(2006) Journal of the Mechanics and Physics of Solids, 54 (11), pp. 2330-2353. Cited 10 times.
https://www.scopus.com/inward/record.uri?eid=2-s2.0-33749665117&doi=10.1016%2fj.jmps.2006.06.008&partnerID=40&md5=2d4f3899e625c809337fb51e523f7d0d

DOI: 10.1016/j.jmps.2006.06.008

ABSTRACT: Recently, we found that a new form of coupled instability, named ThermoElastic Dynamic Instability (TEDI), can occur by interaction between frictional heating and the natural dynamic modes of sliding bodies. This is distinct from the classical dynamic instabilities (DI) which is produced by an interaction between the frictional forces at the sliding interface and the natural modes of vibration of the bodies if the friction coefficient is sufficiently high, and also from ThermoElastic Instability (TEI), which is due to the interaction of frictional heating and thermal expansion, leading for example to low pitched brake noise above some critical speed. This result was relative to an highly idealized system, comprising an elastic layer sliding over a rigid plane including both dynamic and thermoelastic effects, but neglecting shear waves at the interface due to frictional tractions (from which the denomination "frictionless TEDI"). We demonstrate here that including these shear waves destabilizes both the shear and dilatational vibration modes of the system at arbitrarily small friction coefficients and speeds, where DI and TEI are predicted to be stable. A detailed study of the new modes and transient simulations show that for low pressures and high speed, the system tends towards the results of the previous model ("frictionless TEDI"), i.e. the tendency to a state in which the layer bounces over the plane, with alternating periods of sliding contact and separation. In the case of low speeds and high pressures, viceversa, the system is dominated by the modes near the resonance of the shear and dilatational modes, with a resulting complex behaviour, but generally leading to stick-slip regimes, reducing the jumping mode of "frictionless TEDI", because stick reduces or stops frictional heating production.

Afferrante, L., Ciavarella, M.
TEDI (ThermoElasto-Dynamic Instability): A new mechanism for squeal & TEI
(2006) Lecture Notes in Applied and Computational Mechanics, 2006 (27), pp. 231-241.
https://www.scopus.com/inward/record.uri?eid=2-s2.0-33749036888&doi=10.1007%2f3-540-31761-9_26&partnerID=40&md5=3981f49f12f21391d7ff25c77609263c

DOI: 10.1007/3-540-31761-9_26
ABSTRACT: A new mechanism of dynamic instability is found, generated by the thermo-elastic deformations. In particular, it is found that even if coupling between dynamics and heat transfer seems apparently very weak (due to the very different time scales involved), the dynamic modes become unstable for arbitrarily small speeds, in a simple model involving an elastic layer compressed between two rigid plates and sliding out-of-plane. The present analysis neglects the effect of out-of plane deformations and possible stick-slip in that direction.

Ciavarella, M.
Some observations on the CLNA model in fretting fatigue
(2006) Tribology International, 39 (10), pp. 1142-1148. Cited 7 times.
https://www.scopus.com/inward/record.uri?eid=2-s2.0-33746652178&doi=10.1016%2fj.triboint.2006.02.032&partnerID=40&md5=a2a0b9bf2b557413796c10be11363940

DOI: 10.1016/j.triboint.2006.02.032
ABSTRACT: Using the Atzori-Lazzarin criterion, the author has recently proposed a unified model for Fretting Fatigue denominated Crack-Like Notch Analogue-CLNA model, considering only two possible behaviours: either "crack-like" or "large blunt notch". In a general FF condition, the former condition is treated with a single contact problem corresponding to the MIT Crack Analogue (CA) improved in some details also by the author. The latter, with a simple peak stress condition, i.e. a simple Notch Analogue model, simply stating that below the fatigue limit, infinite life is predicted for any size of contact. In the typical condition of constant normal load and in phase oscillating tangential and bulk loads, both limiting conditions are immediately written, and the CLNA model permits to collapse the effect of the contact loads on a single closed form equation (differently from many other models which do not permit this flexibility). For not too large contact areas ("crack-like" contact) no dependence at all on geometry is predicted, but only on 3 load factors (bulk stress, tangential load and average pressure) and size of

the contact. Only in the "large blunt notch" region occurring typically only at very large sizes of contact does size-effect disappear, but the dependence on all other factors including geometry remains. The model compares favourably with some experimental results in the literature. In this paper, some aspects of the CLNA model are further elucidated.

Ciavarella, M., Monno, F.
On the possible generalizations of the Kitagawa-Takahashi diagram and of the El Haddad equation to finite life
(2006) International Journal of Fatigue, 28 (12), pp. 1826-1837. Cited 40 times.
https://www.scopus.com/inward/record.uri?eid=2-s2.0-33748416600&doi=10.1016%2fj.ijfatigue.2005.12.001&partnerID=40&md5=a43ed2388e830e03b5dc7b5109601be2

DOI: 10.1016/j.ijfatigue.2005.12.001
ABSTRACT: The celebrated Kitagawa-Takahashi (KT) diagram, and the El Haddad (EH) equation, have received great attention since they define quite successfully the region of non-propagation (or the condition of self-arrest) for short to long cracks. The EH equation can be also seen as an "asymptotic matching" between the fatigue limit and the threshold of crack propagation. Above this curve, finite life is expected, since cracks propagate and eventually lead to final failure. In this paper, possible extensions of the EH equation to give the life of a specimen with a given initial crack as a function of the applied stress range, using only "asymptotic matching" equation between known regimes, namely the Wöhler SN curve (or some simplified form, like Basquin law), and the crack propagation rate curve (or just the Paris' law). This permits an extension of the so-called "intrinsic crack" size concept in the EH equation for infinite life. The generalized El Haddad equation permits to take into account approximately of some of the known deviations from the Paris regimes, for short cracks, near the fatigue threshold or fatigue limit, or to the static failure envelope. The new equations are also plotted as SN curves, showing that power-law regimes seem very limited with many possible deviations and truncations, even when the crack propagation law has a significant power-law regime. The diagram remains partly qualitative (for example, we neglect geometric factors), and can be considered a first attempt towards more realistic maps. Particularly interesting are the cases with the Paris exponent $m < 2$, in which propagation tends to be very slow until very close to the toughness failure, making the maps qualitatively different. © 2006 Elsevier Ltd. All rights reserved.

Ciavarella, M., Delfine, V., Demelio, V.
A new 2D asperity model with interaction for studying the contact of multiscale rough random profiles
(2006) Wear, 261 (5-6), pp. 556-567. Cited 26 times.
https://www.scopus.com/inward/record.uri?eid=2-s2.0-33747777788&doi=10.1016%2fj.wear.2006.01.028&partnerID=40&md5=31aad0d79e59e1286c177bf88e102f00

DOI: 10.1016/j.wear.2006.01.028
ABSTRACT: Although in principle simple and neat results are obtained with the classical Greenwood-Williamson (GW) model, linearity of real contact area and conductance with load, the GW definition of asperities as local maxima of the surface leads to paradoxical results for multiscale surfaces, as suspected already by Greenwood in a recent self-assessment of his theory, mainly because of interaction effects becoming increasingly important when the density of asperity grows. In the present paper, a new 2D asperity model, with interaction taken into account to the first order, is introduced for a periodic arrangement of asperities, using the Westergaard solution (rather than the isolated Hertzian solution) leading to a non-linear system of equations, which is easily solved iteratively. The use of Westergaard's solution also elegantly solves the problem of the unknown rigid body motion of 2D elasticity. Using the Weierstrass series profile, some example cases for fractals are discussed. The asperities are defined as parabolic functions, either near the GW "peaks", or by the alternative Aramaki-Majumbdar-Bhushan (AMB) definition based on the geometrical intersection at a given separation. The former

method (GW asperities used in the numerical code) gives quite accurate results, except for the contact area and small separations for the case of low fractal dimensions D, i.e. at very large bandwidth parameter. The latter method (AMB) gives generally no significant advantage, since results tend to be discontinuous and not necessarily the physics of the process is captured correctly. It is confirmed that interaction effects are the key missing ingredient of classical asperity models, but also that most quantities (like contact area, load and conductance) depend more on interaction for cases of a given separation, than for a given load. Also, despite the contact area does not depend much on interaction effects, for a given load, the conductance does.

Adams, G.G., Barber, J.R., Ciavarella, M., Rice, J.R.
Closure to "discussion of 'a paradox in sliding contact problems with friction' " (2006, ASME J. Appl. Mech., 73, pp. 884-886)
(2006) Journal of Applied Mechanics, Transactions ASME, 73 (5), p. 887.
https://www.scopus.com/inward/record.uri?eid=2-s2.0-33748415066&doi=10.1115%2f1.2202856&partnerID=40&md5=ad3696b387cb25b5b7da33f92647bffa

DOI: 10.1115/1.2202856

Ciavarella, M., Baldini, A., Barber, J.R., Strozzi, A.
Reduced dependence on loading parameters in almost conforming contacts
(2006) International Journal of Mechanical Sciences, 48 (9), pp. 917-925. Cited 37 times.
https://www.scopus.com/inward/record.uri?eid=2-s2.0-33745052646&doi=10.1016%2fj.ijmecsci.2006.03.016&partnerID=40&md5=80738abe91330fe563dfa65e46cbdfbb

DOI: 10.1016/j.ijmecsci.2006.03.016
ABSTRACT: In cases of completely conforming frictionless contact, the contact area generally either decreases or stays the same under load, in which case the extent of the contact area is subsequently independent of load and the stress and displacement fields vary linearly with the loading parameter. Dundurs and Stippes describe such cases as receding contact problems. Here, we demonstrate that similar results apply in the presence of Coulomb friction, in which case the extent of the stick and slip zones and the local direction of sliding are independent of load. We also show that if there is a small initial gap or interference throughout the potential contact area, the extent of the contact area and the stress and displacement fields will approach those of the corresponding receding contact problem as the applied load is increased. If the interface conditions permit adhesion between the contacting surfaces, the extent of the adhesion zone shrinks to zero as the load increases without limit. Progress of the contact configuration towards the limit is governed solely by a dimensionless load factor involving the ratio between the applied load and the initial clearance or interference. This permits results for a variety of initial geometries (due to tolerance variations) to be obtained from a set of finite element results for a single case. Some of these characteristics are demonstrated using a finite element solution of a connecting rod/bushing/gudgeon pin contact. Other interesting applications are those with complex geometries, ranging from biomechanics, as in prostheses, to the design of multiple fasteners.

Afferrante, L., Ciavarella, M., Valenza, E.
Is Weibull's modulus really a material constant? Example case with interacting collinear cracks
(2006) International Journal of Solids and Structures, 43 (17), pp. 5147-5157. Cited 53 times.
https://www.scopus.com/inward/record.uri?eid=2-s2.0-33745948902&doi=10.1016%2fj.ijsolstr.2005.08.002&partnerID=40&md5=bbd9424433d2a9bd62a0a15fa25693ef

DOI: 10.1016/j.ijsolstr.2005.08.002

ABSTRACT: The Weibull distribution is widely used to describe the scatter of the strength in brittle (but also quasi-brittle) materials, often assuming that the Weibull modulus is a "material constant". One possible motivation of this perhaps comes from the classical Freudenthal's interpretation of Weibull modulus depending on the crack size distribution, which however assumes the cracks to be at large distance one from the other. It is here found with simple numerical experiments with collinear cracks that Weibull distributions tend to be obtained also with interaction taken into account, but the Weibull modulus depends on both the crack size distribution and the distribution of ligaments. Hence, Weibull modulus should not be considered a "material constant" or to correspond to an "intrinsic" microstructure of the material, as assumed in many industrial applications and commercial postprocessors of FEM softwares, even in the case of a varying stress fields. In the limit case of a crack or sharp notch this leads to paradoxically a zero scale parameter (and the usual Weibull modulus). Hence, in the case of a blunt notch, we suggest the Weibull modulus would vary depending on the distribution of cracks, their distances, and the interaction with the geometry and stress field. Only numerical simulations where the distribution of cracks is directly included in the geometry under consideration can provide the correct scale factor and Weibull modulus.

Ciavarella, M., Monno, F., Demelio, G.
On the Dang Van fatigue limit in rolling contact fatigue
(2006) International Journal of Fatigue, 28 (8), pp. 852-863. Cited 31 times.
https://www.scopus.com/inward/record.uri?eid=2-s2.0-33646536811&doi=10.1016%2fj.ijfatigue.2005.11.002&partnerID=40&md5=cc56a5a0552f365dbc4147ce8d2ef062

DOI: 10.1016/j.ijfatigue.2005.11.002
ABSTRACT: Recently, various methods have been proposed to assess the risk of rolling contact fatigue failure and in particular, the Dang Van multiaxial fatigue criterion has been suggested in a simple approximate formulation by Ekberg, Kabo and Andersson. In a recent note by Ciavarella and Maitournam, it was found that the approximation is only valid in a restricted range of cases. Here, a much larger range of conditions including elliptical contact and partial slip conditions are considered and analytical formulae are also derived. The Ekberg, Kabo and Andersson calculation is shown to be a good approximation only for nearly circular contacts, high Poisson's ratio and high Dang Van constant. The Dang Van fatigue limits are very high, particularly for line contact: however, under those conditions ratcheting deformations also are likely to occur unless perhaps for very hard materials showing cyclic yield limit much higher than fatigue limit (these materials in turn could then show very low wear and be prone to fatigue crack propagation). Classical findings about the RCF fatigue suggest nearly twice higher fatigue limit in point contact with respect to line contact conditions, and this is apparently in contradiction to the Dang Van criterion. A possible qualitative explanation is that in point contact above elastic shakedown there is a regime of cyclic plasticity, rather than the direct transition to ratcheting regime as in line contact. However, the Dang Van criterion has been found to be possibly too conservative under RCF also by other authors recently, and further investigations are required.

Ponter, A.R.S., Chen, H.F., Ciavarella, M., Specchia, G.
Shakedown analyses for rolling and sliding contact problems
(2006) International Journal of Solids and Structures, 43 (14-15), pp. 4201-4219. Cited 32 times.
https://www.scopus.com/inward/record.uri?eid=2-s2.0-33744801673&doi=10.1016%2fj.ijsolstr.2005.05.046&partnerID=40&md5=2bfc294a09a7e2c4d48cfcbba42583a2

DOI: 10.1016/j.ijsolstr.2005.05.046
ABSTRACT: There is a range of problems where repeated rolling and sliding contact occurs over a half space of an elastic-perfectly plastic material. For such problems shakedown and limit analysis provide significant advantages over other forms of analysis when a global understanding of deformation behaviour is required. In this

paper, a recently developed numerical upper bound method, the Linear Matching Method (LMM), for shakedown analyses is applied to the solution of a problem previously considered by Ponter et al. [Ponter, A.R.S., Hearle, A.D., Johnson, K.L., 1985. J. Mech. Phys. Solids 33 (4), 339-362] for a moving Hertzian contact, with sliding friction. This semi-analytic solution is an upper bound based on certain specific kinematic assumptions. We show that the Ponter, Hearle and Johnson solution is a reasonable approximate solution for a circular contact area but is less accurate for an elliptic contact area. For an elliptic contact area LLM solutions converge to the line contact solution. The effect of the non-coincidence of the direction of travel and slide is also investigated.

Pugno, N., Ciavarella, M., Cornetti, P., Carpinteri, A.
A generalized Paris' law for fatigue crack growth
(2006) Journal of the Mechanics and Physics of Solids, 54 (7), pp. 1333-1349. Cited 188 times.
https://www.scopus.com/inward/record.uri?eid=2-s2.0-33646479019&doi=10.1016%2fj.jmps.2006.01.007&partnerID=40&md5=26e37296f026aec738654a07d7c8f8cf

DOI: 10.1016/j.jmps.2006.01.007
ABSTRACT: An extension of the celebrated Paris law for crack propagation is given to take into account some of the deviations from the power-law regime in a simple manner using the Wöhler SN curve of the material, suggesting a more general "unified law". In particular, using recent proposals by the first author, the stress intensity factor K(a) is replaced with a suitable mean over a material/structural parameter length scale Δa, the "fracture quantum". In practice, for a Griffith crack, this is seen to correspond to increasing the effective crack length of Δa, similarly to the Dugdale strip-yield models. However, instead of including explicitly information on cyclic plastic yield, short-crack behavior, crack closure, and all other detailed information needed to eventually explain the SN curve of the material, we include directly the SN curve constants as material property. The idea comes as a natural extension of the recent successful proposals by the first author to the static failure and to the infinite life envelopes. Here, we suggest a dependence of this fracture "quantum" on the applied stress range level such that the correct convergence towards the Wöhler-like regime is obtained. Hence, the final law includes both Wöhler's and Paris' material constants, and can be seen as either a generalized Wöhler's SN curve law in the presence of a crack or a generalized Paris' law for cracks of any size.

Afferrante, L., Ciavarella, M., Demelio, G.
On the stress concentration around a hole in a half-plane subject to moving contact loads
(2006) International Journal of Solids and Structures, 43 (13), pp. 3895-3904. Cited 3 times.
https://www.scopus.com/inward/record.uri?eid=2-s2.0-33646406825&doi=10.1016%2fj.ijsolstr.2005.05.003&partnerID=40&md5=0521eecfa65f1eaf638edfe1fdc0489e

DOI: 10.1016/j.ijsolstr.2005.05.003
ABSTRACT: We study the stress concentration due to a pore in an elastic half-plane, subject to moving contact loading, in the entire range of possible geometrical parameters (contact area/hole diameter, hole depth/hole diameter). Since the number of cases is very large to study with FEM even with modern machines, the use of a recent simple approximate formula due to Greenwood based on the stress field in the absence of the hole is first attempted, and compared with a full FEM analysis in sample cases. To further distillate the effects of the hole distance from the free surface and of the contact area size, the limiting cases are studied of: (i) concentrated load perpendicular to the surface and aligned with the hole centre; (ii) constant unit pressure on the top surface of the half-plane and (iii) hydrostatic load. A full investigation is then conduced for the case of Hertzian load on the surface, and it is seen that the tensile stress concentration is significantly reduced with respect to that of the concentrated load, when the contact area size is of the same order of the hole radius. Results obtained with the

approximate Greenwood formula are generally accurate however only if the hole distance from the surface is greater than two times the hole radius. © 2005.

Ciavarella, M., Leoci, F.
An assessment of the Greenwood-Williamson and other asperities models with, special reference to electrical conductance
(2006) Journal of Tribology, 128 (1), pp. 10-17. Cited 15 times.
https://www.scopus.com/inward/record.uri?eid=2-s2.0-33645792658&doi=10.1115%2f1.2125947&partnerID=40&md5=c6153286874788641e5cedf70220deec

DOI: 10.1115/1.2125947
ABSTRACT: Although in principle simple and neat results are obtained with the classical Greenwood-Williamson (GW) model (linearity of real contact area and conductance with load), the definition of asperity as local maxima of the surface leads to uncertain results for multiscale surfaces, as suspected already by Greenwood in a recent self-assessment of his theory [Greenwood, J. A., and Wu, J.J., 2001, "Surface roughness and contact: an apology, "Meccanica 36(6), pp. 617-630]. Quoting the conclusions in the latter paper "The introduction by Greenwood and Williamson in 1966 of the definition of a 'peak' as a point higher than its neighbours on a profile sampled at a finite sampling interval was, in retrospect, a mistake, although it is possible that it was a necessary mistake". Greenwood and Wu suggest that an alternative definition of asperity captures the mechanics of the contact more correctly, that of Aramaki-Majumbdar-Bhushan (AMB). Here, numerical experiments confirm that with a Weierstrass series fractal profile (taken as a 2D slice of a true fractal surface but then used to define a set of circular asperities), load and conductance for numerically measured asperities defined "à la Greenwood-Williamson" (3PP, 3-point peaks) differ significantly from the results obtained with the Aramaki-Majumbdar-Bhushan definition of asperity. The AMB definition, which is based on the bearing area intersection best parabola fitting, gives finite limits for all quantities and varies very little with small scale terms, and tends to coincide with the 3PP method only at unrealistically large fractal dimensions D, or at unrealistically large separations. However, it remains unclear how the AMB results compare with the proper treatment of the problem when interaction effects are fully taken into account. Copyright © 2006 by ASME.

Afferrante, L., Ciavarella, M.
On ratchetting-based models of wear and rolling contact fatigue (RCF)
(2006) Materialpruefung/Materials Testing, 48 (3), pp. 85-89. Cited 1 time.
https://www.scopus.com/inward/record.uri?eid=2-s2.0-33645319234&doi=10.3139%2f120.100713&partnerID=40&md5=7d81cb0b02f9e71ca6e6e1232dfa6188

DOI: 10.3139/120.100713
ABSTRACT: Recent efforts to develop simple unified models of both wear and rolling contact fatigue (Kapoor et al. [1], Franklin et al. [2]) are discussed, in view of previous theoretical and experimental results on ratchetting in rolling contact. It is shown that ratchetting in rolling contact is a combination of "structural ratchetting" (that modelled with the perfect plasticity model) and "material ratchetting", and the latter is very sensitive to the hardening behaviour of the material. Also, rolling contact fatigue at large number of cycles in the Clayton and Su experiments [3, 4] seems not well correlated with shakedown theory, and accordingly, simple ratchetting equations based on excess of shakedown such as that of Tyfoor et al. [5], do not seem well suited as a Wohler SN life curve. However, these conclusions are only very qualitative as the materials in the two tests are different, and at present empirical separate models for wear and rolling contact fatigue based on hardness of materials and a posteriori data fitting seem the only quantitative way forward for engineering purposes. © Carl Hanser Verlag.

Afferrante, L., Ciavarella, M., Barber, J.R.

Sliding thermoelastodynamic instability
(2006) Proceedings of the Royal Society A: Mathematical, Physical and Engineering Sciences, 462 (2071), pp. 2161-2176. Cited 27 times.
https://www.scopus.com/inward/record.uri?eid=2-s2.0-33749668454&doi=10.1098%2frspa.2006.1676&partnerID=40&md5=8a81c2420e8b08b0e438b86d72b619d3

DOI: 10.1098/rspa.2006.1676
ABSTRACT: Numerous mechanisms can give rise to instabilities and vibrations in sliding systems. These can generally be characterized as either elastodynamic (e.g. 'brake squeal') or thermoelastic. The time-scales of these processes differ considerably, so it is usual to neglect coupling between them, i.e. to neglect thermal effects in elastodynamic analyses and to use the quasi-static approximation in thermoelastic analyses. In the present paper, we consider the potential coupling between them in the simplest possible context-a thermoelastodynamic layer sliding against a rigid plane and constrained to one-dimensional displacements. The results show that although the coupling is extremely weak, it has a destabilizing effect on the natural elastodynamic vibration of the layer at arbitrarily low sliding speeds. A numerical solution of the transient equations below the quasi-static critical speed shows that an initial disturbance grows exponentially until periods of separation develop, after which the system approaches asymptotically to a steady state involving periods of contact and separation alternating at the lowest natural frequency of the elastodynamic system. With increasing sliding speed, the proportion of the cycle spent in contact is reduced and the maximum contact pressure increases. It is important to note that neither a quasi-static thermoelastic analysis, nor an elastodynamic analysis neglecting thermal expansion would predict instability in this speed range. Similar instabilities due to thermoelastodynamic coupling are almost certain to occur in more complex practical sliding systems such as brakes and clutches, implying the need for the incorporation of these effects in commercial analysis software. The proposed mechanism might also provide an explanation of reported experimental observations of vibrations normal to the contact interface during frictional sliding. © 2006 The Royal Society.

Ciavarella, M., Strozzi, A., Baldini, A., Giacopini, M., Rivasi, S., Rosi, R.
On the applicability of the loading parameter φ in pinned connections with relevant initial clearance
(2006) Applied Mechanics and Materials, 5-6, pp. 155-164. Cited 4 times.
https://www.scopus.com/inward/record.uri?eid=2-s2.0-33749340595&doi=10.4028%2fwww.scientific.net%2fAMM.5-6.155&partnerID=40&md5=52c79aecd15fdcad1188256bc519b41d

DOI: 10.4028/www.scientific.net/AMM.5-6.155
ABSTRACT: In pinned connections, the presence of an initial clearance increases the lug stress concentration with respect to a neat fit configuration. By employing a recently proposed loading parameter O valid for plane models, the applied load and initial clearance effects on the stress concentration are normalised for a straight-shanked, round-ended, longitudinally loaded pin-lug connection of fixed outer to inner radius ratio. Results are obtained with a Mitchell-type, Fourier series solution and with commercial Finite Elements. The applicability of the loading parameter φ to pinned connections with small to relevant initial clearances is explored. Two preliminary design charts are presented, which quantify the lug stress concentration factor versus the loading parameter φ for two lug geometries defined by inner to outer radii ratios of 0.376 and 0.77.

Ciavarella, M., Dini, D.
A refined CLNA model in fretting fatigue using asymptotic characterization of the contact stress fields
(2005) Fatigue and Fracture of Engineering Materials and Structures, 28 (12), pp. 1099-1112. Cited 7 times.
https://www.scopus.com/inward/record.uri?eid=2-s2.0-30744472218&doi=10.1111%2fj.1460-2695.2005.00948.x&partnerID=40&md5=1100246f1d56f2467038969b27abd5a9

DOI: 10.1111/j.1460-2695.2005.00948.x
ABSTRACT: Using the Atzori-Lazzarin criterion, the first author has recently proposed a unified model for fretting fatigue (FF), called the crack-like notch analogue (CLNA) model. Two possible types of behaviour were suggested: either 'crack-like' or 'large blunt notch,' and these are immediately studied in the typical condition of constant normal load and in phase oscillating tangential and bulk loads. The former condition ('crack-like') was treated by approximating the geometry to the perfectly flat one of the crack analogue (CA), improved in some details, reducing all possible geometries to a single contact problem. The latter ('large blunt notch'), with a simple peak stress condition i.e. a simple notch analogue model. In the present paper, the calculation of the 'crack-like' behaviour is improved using the recent asymptotic characterisation developed by Dini, Hills and Sackfield, which extracts the asymptotic singular stress field of the fretting contact. A significant difference is found in the 'equivalent' geometric factor obtained for the Hertzian geometry, particularly near full sliding, where the new criterion is more conservative, but still not large enough to permit to find, for example in Nowell's FF experimental data, if the refinement is an improvement of predictive capabilities. In flatter geometries, the difference is expected to be even smaller than in the case of the Hertzian geometry, and in this case, the original CLNA model, for its simplicity, remains a very convenient simple closed form criterion.

Ciavarella, M., Afferrante, L., Valenza, E.
Effect of interaction between collinear cracks on the strength distribution of brittle materials
(2005) 11th International Conference on Fracture 2005, ICF11, 2, pp. 939-944. Cited 2 times.
https://www.scopus.com/inward/record.uri?eid=2-s2.0-84869779026&partnerID=40&md5=5388de454afc39f5b9084dee980dd82e

ABSTRACT: Weibull theory neglects interaction between the defects and between defects and stress field, and accordingly obtains that the strength of a material follows a Weibull distribution whose modulus is a material constant, and whose mean value only is affected by the geometry and loading condition. For the limit case of a cracked structure, this corresponds to a paradoxical zero mean strenght. A full account of interaction requires direct Montecarlo simulations (each elasticity problem being solved by an efficient dual boundary element formulation) and shows that mean value and scatter deviate from the theoretical ones. A simple geometry has been considered where an infinite plate uniform remote tension $\sigma\infty$, containing N collinear cracks with statistical distribution of sizes and spacings.

Passeri, D., Bettucci, A., Germano, M., Rossi, M., Alippi, A., Orlanducci, S., Terranova, M.L., Ciavarella, M.
Effect of tip geometry on local indentation modulus measurement via atomic force acoustic microscopy technique
(2005) Review of Scientific Instruments, 76 (9), art. no. 093904, . Cited 52 times.
https://www.scopus.com/inward/record.uri?eid=2-s2.0-25844437506&doi=10.1063%2f1.2044607&partnerID=40&md5=9761bc655344d7bb6064d6ff241f7f38

DOI: 10.1063/1.2044607
ABSTRACT: Atomic force acoustic microscopy (AFAM) is a dynamical AFM-based technique very promising for nondestructive analysis of local elastic properties of materials. AFAM technique represents a powerful investigation tool in order to retrieve quantitative evaluations of the mechanical parameters, even at nanoscale. The quantitative determination of elastic properties by AFAM technique is strongly influenced by a number of experimental parameters that, at present, are not fully under control. One of such issues is that the quantitative evaluation require the knowledge of the tip geometry effectively contacting the surface during the measurements. We present and discuss an experimental approach able to determine, at first, tip geometry from contact stiffness measurements and, on the basis of the achieved information, to measure sample indentation modulus. The reliability and the accuracy of the technique has been successfully tested on samples (Si, GaAs, and InP) with

very well known structural and morphological properties and with indentation modulus widely reported in literature.

Afferrante, L., Ciavarella, M.
Separated steady state solutions for two thermoelastic half-planes in contact with out-of-plane sliding
(2005) Journal of the Mechanics and Physics of Solids, 53 (7), pp. 1449-1475. Cited 5 times.
https://www.scopus.com/inward/record.uri?eid=2-s2.0-18444389979&doi=10.1016%2fj.jmps.2005.02.005&partnerID=40&md5=bb0f4eaaca5e034a19cf6cd8397d6639

DOI: 10.1016/j.jmps.2005.02.005
ABSTRACT: When two materials are placed in contact along an interface, thermoelastic effects can separate the surfaces and create "hot spots" when there is sufficient frictional heating fVp generated at the interface, even if the two surfaces are nominally flat. Additionally, heat can flow because the bodies are generally at different temperatures, and this is an independent cause of separation, generally when heat flows into the less distortive material. These two effects have been considered separately, and here we consider the case with interaction of the two effects, showing possible non-existence, multiplicity and instability of solutions. Approximate Hertzian solutions for the separated contact regime are very limited, particularly for the frictional heating case. Hence, a new efficient full numerical solution is developed, and compared with direct FEM results, the latter permitting also the assessment of stability in the transient regime. Connection to previous results for simple rod models is made. The case of heat flow into the more distortive material is discussed. © 2005 Elsevier Ltd. All rights reserved.

Ciavarella, M., Demelio, G., Murolo, C.
A numerical algorithm for the solution of two-dimensional rough contact problems
(2005) Journal of Strain Analysis for Engineering Design, 40 (5), pp. 463-476. Cited 7 times.
https://www.scopus.com/inward/record.uri?eid=2-s2.0-23844478211&doi=10.1243%2f030932405X15936&partnerID=40&md5=865a4cab3da13adfd3e1fb4a95f726c1

DOI: 10.1243/030932405X15936
ABSTRACT: In this paper, a numerical algorithm is developed to solve the elastic contact problem accurately for two-dimensional rough surfaces. A first version of the method gives a full numerical solution for the discrete problem with all the details of the profile included, and the second version simulates approximately the roughness on a smaller scale with the presence of a non-linear elastic layer (as in the classical Winkler foundation model). In the literature, usually the solution of line contact is given by assuming displacements relative to a datum point, to overcome the difficulty that in two dimensions the displacements are undefined to an arbitrary constant. In the present work, the compliance matrix of the elastic half-plane is calculated starting from a self-equilibrated load distribution with periodic boundary conditions. Some examples are shown to validate the methods. Finally, the method is applied to discuss previous results by the present authors on rough contact problems defined by Weierstrass series profiles, and a discussion follows. In particular, it is found that the Winkler non-linear layer model is surprisingly useful for evaluating the electrical conductance, since (at least in the limited case of two superposed sinusoids) it does not require the wavelength and amplitude of the microscopic component of roughness to be much smaller than the macroscopic component. Some aspects of the mutual role of various components of roughness in the compliance and conductance are elucidated by means of example cases. © IMechE 2005.

Ciavarella, M., Barber, J.R.
Stability of thermoelastic contact for a rectangular elastic block sliding against a rigid wall
(2005) European Journal of Mechanics, A/Solids, 24 (3), pp. 371-376. Cited 17 times.

https://www.scopus.com/inward/record.uri?eid=2-s2.0-19744374629&doi=10.1016%2fj.euromechsol.2004.10.008&partnerID=40&md5=c2111f7144ee7f4bf2fec13868eff3ba

DOI: 10.1016/j.euromechsol.2004.10.008
ABSTRACT: In this note, we determine the stability boundary for the thermoelastic contact of a rectangular elastic block sliding against a rigid wall in the presence of a pressure-dependent thermal contact resistance. This geometry can be seen as intermediate between the idealized 'Aldo' rod model and continuum solutions for the elastic half-plane. The solution is obtained by comparing the expression for the perturbed boundary condition including frictional heating with that for purely static loading, already solved by Yeo and Barber (1995). The critical sliding speed is obtained as a function of the temperature difference imposed between the wall and the free end. In most cases, frictional heating tends to destabilize the system. However, for certain forms of the resistance-pressure law, the opposite conclusion is reached and the system can be stable for all sliding speeds.

Andersson, L.-E., Klarbring, A., Barber, J.R., Ciavarella, M.
On the existence and uniqueness of steady state solutions in thermoelastic contact with frictional heating
(2005) Proceedings of the Royal Society A: Mathematical, Physical and Engineering Sciences, 461 (2057), pp. 1261-1282. Cited 4 times.
https://www.scopus.com/inward/record.uri?eid=2-s2.0-26944501226&doi=10.1098%2frspa.2004.1398&partnerID=40&md5=14b76ec51c109e0b0ae163ae71ae88eb

DOI: 10.1098/rspa.2004.1398
ABSTRACT: It is well known that contact and friction in thermoelasticity result in mathematical problems which may lack solutions or have multiple solutions. Previously, issues related to thermal contact and issues related to frictional heating have been discussed separately. In this work, the two effects are coupled. Theorems of existence and uniqueness of solutions in two or three space dimensions are obtained - essentially extending, to frictional heating, results due to Duvaut, which were built on Barber's heat exchange conditions. Two qualitatively different existence results are given. The first one requires that the contact thermal resistance goes to zero at least as fast as the inverse of the contact pressure. The second existence theorem requires no such growth condition, but requires instead that the frictional heating, i.e. the sliding velocity times the friction coefficient, is small enough. Finally, it is shown that a solution is unique if the inverse of the contact thermal resistance is Lipschitz continuous and the Lipschitz constant, as well as the frictional heating, is small enough.

Adams, G.G., Barber, J.R., Ciavarella, M., Rice, J.R.
A paradox in sliding contact problems with friction
(2005) Journal of Applied Mechanics, Transactions ASME, 72 (3), pp. 450-452. Cited 11 times.
https://www.scopus.com/inward/record.uri?eid=2-s2.0-20444473062&doi=10.1115%2f1.1867992&partnerID=40&md5=1f005fc0dba27e689e69c5e4b37ea462

DOI: 10.1115/1.1867992
ABSTRACT: In problems involving the relative sliding to two bodies, the frictional force is taken to oppose the direction of the local relative slip velocity. For a rigid fiat punch sliding over a half-plane at any speed, it is shown that the velocities of the half-plane particles near the edges of the punch seem to grow without limit in the same direction as the punch motion. Thus the local relative slip velocity changes sign. This phenomenon leads to a paradox in friction, in the sense that the assumed direction of sliding used for Coulomb friction is opposite that of the resulting slip velocity in the region sufficiently close to each of the edges of the punch. This paradox is not restricted to the case of a rigid punch, as it is due to the deformations in the half-plane over which the pressure is

moving. It would therefore occur for any punch shape and elastic constants (including an elastic wedge) for which the applied pressure, moving along the free surface of the half-plane, is singular. The paradox is resolved by using a finite strain analysis of the kinematics for the rigid punch problem and it is expected that finite strain theory would resolve the paradox for a more general contact problem. Copyright © 2005 by ASME.

Afferrante, L., Ciavarella, M.
Instability of thermoelastic contact for two half-planes sliding out-of-plane with contact resistance and frictional heating
(2004) Journal of the Mechanics and Physics of Solids, 52 (7), pp. 1527-1547. Cited 22 times.
https://www.scopus.com/inward/record.uri?eid=2-s2.0-2442490992&doi=10.1016%2fj.jmps.2004.01.003&partnerID=40&md5=b25bca1ac4836bfcefaa699ee5eac0de

DOI: 10.1016/j.jmps.2004.01.003
ABSTRACT: Thermoelastic contact is known to show instabilities when the heat transmitted across the interface depends on the pressure, either because of a pressure-dependent thermal contact resistance R(p) or because of frictional heating due to the product of friction coefficient, speed, and pressure, fVp. Recently, the combined effect of pressure-dependent thermal contact resistance and frictional heating has been studied in the context of simple rod models or for a more realistic elastic conducting half-plane sliding against a rigid perfect conductor "wall". Because R(p) introduces a non-linearity even in full contact, the "critical speed" for the uniform pressure solution to be unstable depends not just on material properties, and geometry, but also on the heat flux and on pressure. Here, the case of two different elastic and conducting half-planes is studied, and frictional heating is shown to produce significant effects on the stability boundaries with respect to the Zhang and Barber (J. Appl. Mech. 57 (1990) 365) corresponding case with no sliding. In particular, frictional heating makes instability possible for a larger range of prescribed temperature drop at the interface including, at sufficiently high speeds, the region of opposite sign of that giving instability in the corresponding static case. The effect of frictional heating is particularly relevant for one material combinations of the Zhang and Barber (J. Appl. Mech. 57 (1990) 365) classification (denominated class b here), as above a certain critical speed, the system is unstable regardless of temperature drop at the interface. Finally, if the system has a prescribed heat flow into one of the materials, the results are similar, except that frictional heating may also become a stabilizing effect, if the resistance function and the material properties satisfy a certain condition.

Ciavarella, M., Murolo, G., Demelio, G.
The electrical/thermal conductance of rough surfaces - The Weierstrass-Archard multiscale model
(2004) International Journal of Solids and Structures, 41 (15), pp. 4107-4120. Cited 37 times.
https://www.scopus.com/inward/record.uri?eid=2-s2.0-2542534551&doi=10.1016%2fj.ijsolstr.2004.02.048&partnerID=40&md5=dd12efb60b34f0abe2b3a6e01ee7079f

DOI: 10.1016/j.ijsolstr.2004.02.048
ABSTRACT: Rough surfaces show a load-dependent electrical constriction resistance. Here, using a recent analogy due to Barber [Proc. R. Soc. London A 459 (2003) 53] between the incremental stiffness and the conductance in the elastic regime, and the Archard hypothesis to solve the multiscale contact problem, the conductance is found for the profile defined by the Weierstrass series. The analysis is also approximately valid, neglecting thermal effects on the contact area, for the thermal conductance.

Ciavarella, M., Murolo, G., Demelio, G., Barber, J.R.
Elastic contact stiffness and contact resistance for the Weierstrass profile
(2004) Journal of the Mechanics and Physics of Solids, 52 (6), pp. 1247-1265. Cited 65 times.

https://www.scopus.com/inward/record.uri?eid=2-s2.0-1642602151&doi=10.1016%2fj.jmps.2003.12.002&partnerID=40&md5=9657e747b49a7ea44077127475c3e9e5

DOI: 10.1016/j.jmps.2003.12.002
ABSTRACT: The Weierstrass series comprises a system of superposed self-affine sine waves that can be used to define a simple idealization of a two-dimensional fractal rough surface profile. The load-compliance relation for the contact of this profile with a rigid plane is here estimated using Westergaard's solution for the contact of a single sine wave with a plane and various approximations concerning the interaction of the different terms in the series. These approximations are compared with a numerical solution for the contact of the profile defined by the first few terms of the series. Once the load-compliance relation is established, the electrical contact resistance can be determined, using an analogy between the conduction and incremental elastic contact problems. The results show that these simple estimates give quite good predictions of the relations between load, compliance and contact resistance. They also confirm that these relations are largely determined by the coarse scale features of the surface profile, in contrast to the predictions of classical asperity model theories.

Afferrante, L., Ciavarella, M.
The thermoelastic Aldo contact model with frictional heating
(2004) Journal of the Mechanics and Physics of Solids, 52 (3), pp. 617-640. Cited 15 times.
https://www.scopus.com/inward/record.uri?eid=2-s2.0-1642382618&doi=10.1016%2fS0022-5096%2803%2900116-9&partnerID=40&md5=b88176bddc32755d698ff45faeac995f

DOI: 10.1016/S0022-5096(03)00116-9
ABSTRACT: In the study of the essential features of thermoelastic contact, Comninou and Dundurs (J. Therm. Stresses 3 (1980) 427) devised a simplified model, the so-called "Aldo model", where the full 3D body is replaced by a large number of thin rods normal to the interface and insulated between each other, and the system was further reduced to 2 rods by Barber's Conjecture (ASME J. Appl. Mech. 48 (1981) 555). They studied in particular the case of heat flux at the interface driven by temperature differences of the bodies, and opposed by a contact resistance, finding possible multiple and history dependent solutions, depending on the imposed temperature differences. The Aldo model is here extended to include the presence of frictional heating. It is found that the number of solutions of the problem is still always odd, and Barber's graphical construction and the stability analysis of the previous case with no frictional heating can be extended. For any given imposed temperature difference, a critical speed is found for which the uniform pressure solution becomes non-unique and/or unstable. For one direction of the temperature difference, the uniform pressure solution is non-unique before it becomes unstable. When multiple solutions occur, outermost solutions (those involving only one rod in contact) are always stable. A full numerical analysis has been performed to explore the transient behaviour of the system, in the case of two rods of different size. In the general case of N rods, Barber's conjecture is shown to hold since there can only be two stable states for all the rods, and the reduction to two rods is always possible, a posteriori.

Ciavarella, M., Meneghetti, G.
On fatigue limit in the presence of notches: Classical vs. recent unified formulations
(2004) International Journal of Fatigue, 26 (3), pp. 289-298. Cited 52 times.
https://www.scopus.com/inward/record.uri?eid=2-s2.0-0344081901&doi=10.1016%2fS0142-1123%2803%2900106-3&partnerID=40&md5=a8e5979ebf3b46c37c3679622c39c828

DOI: 10.1016/S0142-1123(03)00106-3

ABSTRACT: Classical formulations for the fatigue strength reduction factor of notched specimen, Kf, (such as those by Neuber, Peterson, Heywood) were developed long time ago and have found some success by introducing a material constant (dependent on the tensile strength only) in order to take into account the problem of notch sensitivity. However, being empirical fitting equations, they have serious limitations when their asymptotic behaviour is considered, or when the empirical constants are not directly calibrated with experiments. This is shown in this work by using example data taken from the literature for various steels and alloys, and various notch sizes and shapes. Furthermore, although the material constants can be modified to include fatigue threshold dependence (satisfying the requirements of fracture mechanics), only the Neuber formula has a correct functional form in the entire range of notch sizes and shapes, and indeed appears to be sufficiently conservative in the range of data considered. Improved accuracy is found with a more recent empirical criterion due to Atzori and Lazzarin based on the Smith and Miller classification of notches, and with a new criterion here obtained by making consistent the Atzori and Lazzarin with the Lukáš-Klesnil, having a sound interpretation in terms of self-arrested cracks ahead of a rounded notch for which the Creager-Paris stress field is valid. A large number of experimental data are taken from the literature to compare the accuracies of the various criteria.Kf

Afferrante, L., Ciavarella, M.
Frictionally excited thermoelastic instability in the presence of contact resistance
(2004) Journal of Strain Analysis for Engineering Design, 39 (4), pp. 351-357. Cited 11 times.
https://www.scopus.com/inward/record.uri?eid=2-s2.0-3142725491&doi=10.1243%2f0309324041223926&partnerID=40&md5=81642fc13574cfb60ab35008d9d0edb4

DOI: 10.1243/0309324041223926
ABSTRACT: In sliding systems, frictional heating generates a well-known instability above a certain critical speed Kcr, which is a function of geometrical and material properties only. Similar instabilities are known to occur in the static problem, driven by temperature differences, in the presence of thermal contact resistance. Thermal contact resistance at the interface has seldom been considered and gives rise to full coupling of the problem. Generally, the resistance decreases nonlinearly when pressure is increased. Here, the critical condition (in terms of heat flux and sliding speed) for the stability of the uniform pressure solution for a half-plane in frictional contact with a rigid wall at fixed temperature is studied for a general resistance function R(p). It is found that the heat flux direction increases the instability as in the case of zero speed, i.e. when directed into the half-plane (which is the only distortive material), whereas frictional heating can have also a stabilizing effect, for a given heat flux, specifically when R(p) +pR'(p) < 0. Also, an isothermal critical speed has been defined, and the actual critical speed is found to be smaller or larger depending on the temperature difference sign. Longer wavelengths are always more unstable so that the critical wavelength is still dictated by the real size of the system.

Ciavarella, M., Barber, J.R.
Elastic contact stiffness and contact resistance for fractal profiles
(2004) Proceedings of the ASME/STLE International Joint Tribology Conference, IJTC 2004, (PART A), art. no. TRIB2004-64357, pp. 103-106. Cited 1 time.
https://www.scopus.com/inward/record.uri?eid=2-s2.0-21244431642&doi=10.1115%2ftrib2004-64357&partnerID=40&md5=73c1407a9782e68c5f26f535c444c5c8

DOI: 10.1115/trib2004-64357
ABSTRACT: A recent theorem due to Barber shows an analogy between conductance and incremental stiffness of a contact, implying bounds on conductance based on peak-to-peak roughness. This shows that even a fractal roughness, with bounded amplitude, has a finite conductance. The analogy also permits a simple interpretation of classical results of rough contact models based on independent asperities such as Greenwood-Williamson and

developments. For example, in the GW model with exponential distribution of asperity heights, the conductance is found simply proportional to load, and inversely proportional to a roughness amplitude parameter which does not depend greatly on resolution, contrary to parameters of slopes and curvatures. However, for the Gaussian distribution or for more refined models also considering varying curvature of asperities (such as Bush Gibson and Thomas), there is dependence on sampling interval and the conductance grows unbounded. An alternative choice of asperity definition (Aramaki-Majumdar-Bhushan) is suggested, which builds on the geometrical intersection of the rough surface, with the consequence of a finite contact area, and converging load-separation and load-conductance relationships. A discussion follows, also based on numerical results. Copyright © 2004 by ASME.

Barber, J.R., Ciavarella, M., Afferrante, L.
Influence of thermal contact resistance on frictionally excited thermoelastic instability (TEI)
(2004) Proceedings of the ASME/STLE International Joint Tribology Conference, IJTC 2004, (PART A), art. no. TRIB2004-64367, pp. 123-126. Cited 1 time.
https://www.scopus.com/inward/record.uri?eid=2-s2.0-21244432800&doi=10.1115%2ftrib2004-64367&partnerID=40&md5=6fe851b4f6a5a10d91283643e22b0b7c

DOI: 10.1115/trib2004-64367
ABSTRACT: Thermoelastic contact problems can posess non-unique and/or unstable steady-state solutions if there is frictional heating or if there is a pressure-dependent thermal contact resistance at the interface. These two effects have been extensively studied in isolation, but their possible interaction has not been investigated until recently. We shall discuss some idealized geometries in which the two effects are seen to form limiting cases of a more general stability and existence behavior. In most cases, frictional heating has a destabilizing effect relative to the static contact problem, but if the thermal contact resistance is very sensitive to pressure, cases of stabilization can be obtained. Also, the critical sliding speed depends on the contact pressure in contrast to results obtained in the absence of thermal contact resistance. Copyright © 2004 by ASME.

Ponter, A.R.S., Afferrante, L., Ciavarella, M.
A note on Merwin's measurements of forward flow in rolling contact
(2004) Wear, 256 (3-4), pp. 321-328. Cited 10 times.
https://www.scopus.com/inward/record.uri?eid=2-s2.0-1442289344&doi=10.1016%2fS0043-1648%2803%2900407-1&partnerID=40&md5=2ed62dde004fb4675e1bee9e7f45327b

DOI: 10.1016/S0043-1648(03)00407-1
ABSTRACT: The first quantitative analysis of the forward flow in frictionless rolling contact, firstly discovered experimentally by Crook [Proc. Inst. Mech. Eng. London 171 (1957) 187], was conducted by Merwin [Plastic deformation of surfaces in rolling, Ph.D. Dissertation, Cambridge University, UK, 1962] who attempted to model the ratchetting phenomenon in excess of shakedown (the cumulative forward flow due to continuous shear strain increase observed in experiments) as a function of load using a simple perfect plasticity model and a simplified solution to the elasto-plastic problem. However, later FEM analysis [J. Appl. Mech., Trans. ASME 52 (1985) 67, 75] and more refined calculations still based on perfect plasticity but using distributed dislocations [J. Mech. Phys. Solids 33 (1987) 61], found that the ratchet rate was much higher than what measured in experiments, showing the Merwin's approximate solution method was not effective. However, later analysis have concentrated on sophisticated non-linear hardening laws, also because the ratchetting strain rate was found to slowly decay in rail steel materials. This note is focused on another, less known, aspect of the original Merwin's analysis: his material data were limited to monotonic curves, but his yield limit choice corresponds for around 1% for mild steel and Dural, but to nearly 25% deformation in copper, indicating that hardening plays a significant role into the mechanics of the problem, and that Merwin had taken this into account a posteriori by looking at the load where ratchetting begins. The paper suggests that the cyclic strain growth can be divided into two sequential

phenomena: the first, assuming there is no long term material ratchetting (MR), i.e. a calculation based upon elastic properties and a monotonic stress-plastic strain curve, and a second, steady state, for a hardened structure, depending only on MR. In the first phase, we assume the plastic flow is dominated by structural ratchetting (SR), i.e. assuming the ratchetting is well described by the perfectly plastic prediction, where the yield limit is increased according to the level of deformation. This process leads to a quick saturation and the following deformation is attributed to the steady-state material response which we denominate MR. Further, it is shown that experimental measurements of Merwin have more to do with MR than SR.

Afferrante, L., Ciavarella, M., Demelio, G.
A re-examination of rolling contact fatigue experiments by Clayton and Su with suggestions for surface durability calculations
(2004) Wear, 256 (3-4), pp. 329-334. Cited 12 times.
https://www.scopus.com/inward/record.uri?eid=2-s2.0-1442264824&doi=10.1016%2fS0043-1648%2803%2900408-3&partnerID=40&md5=01dcf0b18c4a8b19262247745a88e91e

DOI: 10.1016/S0043-1648(03)00408-3
ABSTRACT: A re-interpretation of recent RCF experiments by Clayton and Su (C&S) [Wear 200 (1996) 63] under water lubricated rolling/sliding conditions, with careful measurements of ratchetting strains, and their comparisons with experimentally observed lives, seems to confirm the validity of ratchetting failure (RF) mechanism and Kapoor's "critical ratchet strain" as a material property. However, the complexity of modelling the ratchetting phenomenon and the uncertainties on the material's critical ratchet strain, suggests that perhaps a more realistic alternative is the use of empirical Wöhler-like life curves similarly to currently used for the contact fatigue evaluation in gears design and standards. In particular, it is found that the "pitting" fatigue limit at 107 cycles suggested by the gears standard is reasonably accurate also for the C&S experiments on various typical rail steels. Since the gears life factor suggested for gears turns out quite conservative at shorter lives, it seems a single new life factor could be suggested, at least for all pearlitic and bainitic steels tested by C&S under water lubrication.

Ciavarella, M., Maitournam, H., Ekberg, A., Kabo, E., Andersson, H.
On the Ekberg, Kabo and Andersson calculation of the Dang Van high cycle fatigue limit for rolling contact fatigue (multiple letters)
(2004) Fatigue and Fracture of Engineering Materials and Structures, 27 (6), pp. 523-526. Cited 13 times.
https://www.scopus.com/inward/record.uri?eid=2-s2.0-2442693135&doi=10.1111%2fj.1460-2695.2004.00772.x&partnerID=40&md5=f52d1f138f84df51a2371d2ca0e5b1cd

DOI: 10.1111/j.1460-2695.2004.00772.x
ABSTRACT: Recently, various methods have been proposed to assess the risk of rolling contact fatigue failure by Ekberg, Kabo and Andersson, and in particular, the Dang Van multiaxial fatigue criterion has been suggested in a simple approximate formulation. In this note, it is found that the approximation implied can be very significant; the calculation is improved and corrected, and focused on the study of plane problems but for a complete range of possible friction coefficients. It is found that predicted fatigue limit could be much higher than that under standard uniaxial tension/compression for 'hard materials' than for 'ductile materials.' This is in qualitative agreement, for example, with gears' design standards, but in quantitative terms, particularly for frictionless condition, the predicted limit seems possibly too high, indicating the need for careful comparison with experimental results. Some comments are devoted to the interplay of shakedown and fatigue.

Ciavarella, M.

A 'crack-like' notch analogue for a safe-life fretting fatigue design methodology
(2003) Fatigue and Fracture of Engineering Materials and Structures, 26 (12), pp. 1159-1170. Cited 41 times.
https://www.scopus.com/inward/record.uri?eid=2-s2.0-0346335674&doi=10.1046%2fj.1460-2695.2003.00721.x&partnerID=40&md5=95335349c02a79bbe68277efc086f0f1

DOI: 10.1046/j.1460-2695.2003.00721.x
ABSTRACT: Various analogies have recently been proposed for comparing the stress fields induced in fretting fatigue contact situations, with those of a crack and a sharp or a rounded notch, resulting in a degree of uncertainty over which model is most appropriate in a given situation. However, a simple recent approach of Atzori-Lazzarin for infinite-life fatigue design in the presence of a geometrical notch suggests a corresponding unified model also for fretting fatigue (called Crack-Like Notch Analogue model) considering only two possible behaviours: either 'crack-like' or 'large blunt notch.' In a general fretting fatigue situation, the former condition is treated with a single contact problem corresponding to a Crack Analogue model; the latter, with a simple peak stress condition (as in previous Notch Analogue models), simply stating that below the fatigue limit, infinite life is predicted for any size of contact. In the typical situation of constant normal load and in phase oscillating tangential and bulk loads, both limiting conditions can be readily stated. Not only is the model asymptotically correct if friction is infinitely high or the contact area is very small, but also remarkably accurate in realistic conditions, as shown by excellent agreement with Hertzian experimental results on Al and Ti alloys. The model is useful for preliminary design or planning of experiments reducing spurious dependences on an otherwise too large number of parameters. In fact, for not too large contact areas ('crack-like' contact) no dependence at all on geometry is predicted, but only on three load factors (bulk stress, tangential load and average pressure) and size of the contact. Only in the 'large blunt notch' region occurring typically only at very large sizes of contact, does the size-effect disappear, but the dependence is on all other factors including geometry.

Vlassak, J.J., Ciavarella, M., Barber, J.R., Wang, X.
The indentation modulus of elastically anisotropic materials for indenters of arbitrary shape
(2003) Journal of the Mechanics and Physics of Solids, 51 (9), pp. 1701-1721. Cited 152 times.
https://www.scopus.com/inward/record.uri?eid=2-s2.0-0041764523&doi=10.1016%2fS0022-5096%2803%2900066-8&partnerID=40&md5=3cca246ffdc1ca71a7250c3524bdbaa3

DOI: 10.1016/S0022-5096(03)00066-8
ABSTRACT: The contact of an indenter of arbitrary shape on an elastically anisotropic half space is considered. It is demonstrated in a theorem that the solution of the contact problem is the one that maximizes the load on the indenter for a given indentation depth. The theorem can be used to derive the best approximate solution in the Rayleigh-Ritz sense if the contact area is a priori assumed to have a certain shape. This approach is used to analyze the contact of a sphere and an axisymmetric cone on an anisotropic half space. The contact area is assumed to be elliptical, which is exact for the sphere and an approximation for the cone. It is further shown that the contact area is exactly elliptical even for conical indenters when a limited class of Green's functions is considered. If only the first term of the surface Green's function Fourier expansion is retained in the solution of the axisymmetric contact problem, a simpler solution is obtained, referred to as the equivalent isotropic solution. For most anisotropic materials, the contact stiffness determined using this approach is very close to the value obtained for both conical and spherical indenters by means of the theorem. Therefore, it is suggested that the equivalent isotropic solution provides a quick and efficient estimate for quantities such as the elastic compliance or stiffness of the contact. The "equivalent indentation modulus", which depends on material and orientation, is computed for sapphire and diamond single crystals.

Ciavarella, M., Macina, G.
New results for the fretting-induced stress concentration on Hertzian and flat rounded contacts

(2003) International Journal of Mechanical Sciences, 45 (3), pp. 449-467. Cited 33 times.
https://www.scopus.com/inward/record.uri?eid=2-s2.0-0037508855&doi=10.1016%2fS0020-7403%2803%2900061-4&partnerID=40&md5=906a4766764a1669aa2098b5af1f2d2d

DOI: 10.1016/S0020-7403(03)00061-4
ABSTRACT: Recent work on fretting fatigue has emphasized the role of stress concentration on fretting damage, while previous work had concentrated on empirical parameters to assess influence of fretting on fatigue life. In particular, analogies with fatigue in the presence of a crack or a notch have been noticed, suggesting that the stress field induced by frictional contact per se may explain the reduction of fatigue life due to fretting. In the paper, new analytical and numerical solutions are produced for the stress concentration induced in typical fretting contacts involving the Hertzian geometry or the flat punch with rounded corners in view of application to the dovetail joints. Normal and tangential load (in the Cattaneo-Mindlin sense) is considered with "moderate" or "large" bulk stresses.

Afferrante, L., Ciavarella, M., Decuzzi, P., Demelio, G.
Thermoelastic instability in a thin layer sliding between two half-planes: Transient behaviour
(2003) Tribology International, 36 (3), pp. 205-212. Cited 11 times.
https://www.scopus.com/inward/record.uri?eid=2-s2.0-0037333673&doi=10.1016%2fS0301-679X%2802%2900185-8&partnerID=40&md5=323311b9b38195ce9bb5ba405b19ae88

DOI: 10.1016/S0301-679X(02)00185-8
ABSTRACT: The susceptibility of brakes and clutches to the known phenomenon of frictionally-excited thermoelastic instability is estimated studying the interface temperature and pressure evolution with time. A simple model has been considered where a layer with half-thickness a slides with speed V between two rigid and non-conducting half-planes. The advantage of this fairly simple model is that it permits us to deduce analytically the critical conditions for the onset of instability, that is the relation between the critical speed Vcr and the growth rate b of the interface temperature and pressure. It has then been verified that as the thickness a reduces the system becomes more and more prone to instability, and that a symmetrical pressure/temperature distribution at the layer interfaces can be more unstable than an antisymmetrical one. Moreover, the analysis of the evolution of the system beyond the critical conditions has shown that even if low frequency perturbations are associated with small critical speed, they might be less critical than high frequency perturbations if the working sliding speed is much larger than the actual critical speed of the system.

Ciavarella, M., Macina, G.
A note on the crack analogue model for fretting fatigue
(2003) International Journal of Solids and Structures, 40 (4), pp. 807-825. Cited 10 times.
https://www.scopus.com/inward/record.uri?eid=2-s2.0-0037319862&doi=10.1016%2fS0020-7683%2802%2900652-2&partnerID=40&md5=03596d09beb6200ed289f40f82d80dbe

DOI: 10.1016/S0020-7683(02)00652-2
ABSTRACT: The contact of a flat punch over a half-plane under constant normal loads, and oscillating tangential and bulk loads is studied, with the aim to improve the crack analogue (CA) model for fretting fatigue (FF) (Acta Mater. 46(9) (1998) 2955). New analytical results are found for a range of conditions, finding the effect of bulk loads and of partial slip which were not considered in the original CA model. Implications for the FF life assessment methodology are found to be significant.

Ciavarella, M., Demelio, G.
An assessment of Archard and Persson's models for the elastic contact of rough surfaces

(2003) Contact Mechanics - Friction: Modeling and Experiment, pp. 163-165.
https://www.scopus.com/inward/record.uri?eid=2-s2.0-1842530536&doi=10.1115%2f2003-trib-0284&partnerID=40&md5=22d99b61df37cd50b772a2c9209eee5c

DOI: 10.1115/2003-trib-0284
ABSTRACT: The Archard and the Persson models for elastic contact of rough surfaces are critically assessed for a Weierstrass series profile, finding that they both do not take into account of redistribution of load and interaction effects fully, unless scales are separated enough.

Ciavarella, M., Afferrante, L.
On ratchetting-based models of wear and rolling contact fatigue (RCF)
(2003) Contact Mechanics - Friction: Modeling and Experiment, pp. 167-172.
https://www.scopus.com/inward/record.uri?eid=2-s2.0-1842530532&doi=10.1115%2f2003-trib-0285&partnerID=40&md5=56e661145528d78e305399437ea03898

DOI: 10.1115/2003-trib-0285
ABSTRACT: Recent efforts to develop simple unified models of both wear and RCF (Kapoor & Franklin, 2000, Franklin et al., 2001) are discussed, in view of previous theoretical and experimental results on ratchetting in rolling contact. At sufficiently high contact pressures, surfaces deform plastically with unidirectional cumulation of "ratchetting" strains (Johnsor., 1985, Ch.9). However, the modelling of ratchetting strains as a function of plastic material properties has turned out more complicated than what originally suggested by the first attempts (Merwin & Johnson, 1963), as recently discussed by Ponter et al. (2003). Wear due to surface ratchetting occurs for sufficiently high friction, whereas RCF is mainly due to ratchetting subsurface. It appears that experimental data on ratchetting strains in the literature unfortunately do not show a clear and unique trend, and various proposed fitting equations differ significantly in quantitative and qualitative terms, particularly at large number of cycles. It is shown that ratchetting in rolling contact is a combination of "structural ratchetting" (that modelled with the perfect plasticity model) and "material ratchetting", and the latter is very sensitive to the hardening behaviour of the material. Also, the surface and subsurface flow regimes are very different: in pure rolling, a simplified model of the stress cycle condition is a fully reversed cycle of shear superposed to an out-of-phase pulsating compression in a extended region below the surface (neglecting other two components also of pulsating compression); increasing the friction coefficient, a mean shear stress is induced as well as a tensile component in the direct stress, and for friction f>0.3 the maximum moves at the surface, but the highly stressed zone becomes a thin surface layer which suffers uniquely of "material ratchetting". In the limit of very high friction, we have the critical condition on the surface which obviously gives a pulsating shear stress cycle in phase with a pulsating compression, but in addition we have a nearly fully reversed cycle of tension-compression (although the tensile peak is very localized also in the longitudinal direction). Such multiaxial stress fields and their largely different features introduced cause a response of the material which has not been studied enough, perhaps both in terms of ratchetting rates and in terms of the failure condition. In particular, the ductility for ratchetting surface flow as used in wear models seems apparently much higher than that for RCF ratchetting models. Also, RCF at large number of cycles in the C&S experiments (Clayton & Su, 1996, Su & day ton, 1997) seems not well correlated with shakedown theory, and accordingly, simple ratchetting equations based on excess of shakedown such as that of Tyfoor et al (1996), do not seem well suited a Wohler SN life curve. However, these conclusions are only very qualitative as the materials in the two tests are different, and at present empirical separate models for wear and RCF based on hardness of materials and a posteriori data fitting seem the only quantitative way forward for engineering purposes.

Ciavarella, M., Decuzzi, P., Tagarielli, V.L., Demelio, G.P.
Simple formulas for thermoelastic stresses in tbc coatings
(2003) Journal of Thermal Stresses, 26 (5), pp. 409-422. Cited 3 times.

https://www.scopus.com/inward/record.uri?eid=2-s2.0-0242443322&doi=10.1080%2f713855940&partnerID=40&md5=003e3293e605f2e05d8b61d48cf8a5b5

DOI: 10.1080/713855940
ABSTRACT: Thin coatings on metallic substrates are extensively used in mechanical, aerospace, microelectronic, optical, and medical applications. Coatings affect the surface properties of the system, while bulk properties and strength primarily depend on the substrate. In coated components subjected to thermal cycling, differences in physical properties and chemical nature between constituent parts of coating and substrate can cause thermal stresses, atomic diffusion, and chemical interactions, which decrease high-temperature stability and actual strength of the system. In this article, the microstructure of a thermal barrier coating is briefly described; then, the temperature field inside the coating is calculated from a transient or a steady periodic state analysis; hence, thermomechanical stresses are analytically determined for a double-layer system with planar or axisymmetric geometry. The present analysis leads to new formulas with which temperature and stress fields can be calculated.

Afferrante, L., Ciavarella, M., Decuzzi, P., Demelio, G.
Transient analysis of frictionally excited thermoelastic instability in multi-disk clutches and brakes
(2003) Wear, 254 (1-2), pp. 136-146. Cited 39 times.
https://www.scopus.com/inward/record.uri?eid=2-s2.0-0037247804&doi=10.1016%2fS0043-1648%2802%2900306-X&partnerID=40&md5=caeea2f11d8933849c76d673adbc1dcd

DOI: 10.1016/S0043-1648(02)00306-X
ABSTRACT: A 2D multilayered model has been considered to estimate the transient evolution of temperature and pressure perturbations in multi-disk clutches and brakes during operation. The model proposed by Decuzzi et al. [1] has been modified here to estimate the variation of b-perturbation growth rate-with V-relative sliding speed. It has been verified that the perturbation with the lowest critical speed has also the highest growth rate, and that low frequency perturbations are less critical than high frequency perturbations, at fixed critical speed. Therefore, when comparing perturbations with identical critical speed, those with higher wave numbers are responsible for more intense thermomechanical damages. Also, for perturbations with wave number smaller than the critical mcr , the temperature increases with m; vice versa for perturbations with wave number larger than mcr the temperature decreases with m. A reduction in thickness ratio a1/a2 between friction and metal disks has the effect of increasing the temperature and growth rate. An approximate formula for the temperature variation with time has been derived for a linearly decreasing engagement speed.

Ciavarella, M., Johansson, L., Afferrante, L., Klarbring, A., Barber, J.R.
Interaction of thermal contact resistance and frictional heating in thermoelastic instability
(2003) International Journal of Solids and Structures, 40 (21), pp. 5583-5597. Cited 35 times.
https://www.scopus.com/inward/record.uri?eid=2-s2.0-0141456222&doi=10.1016%2fS0020-7683%2803%2900313-5&partnerID=40&md5=5cbdffee4b03098a394e6010ed872a2b

DOI: 10.1016/S0020-7683(03)00313-5
ABSTRACT: Thermoelastic contact problems can posess non-unique and/or unstable steady-state solutions if there is frictional heating or if there is a pressure-dependent thermal contact resistance at the interface. These two effects have been extensively studied in isolation, but their possible interaction has never been investigated. In this paper, we consider an idealized problem in which a thermoelastic rod slides against a rigid plane with both frictional heating and a contact resistance. For sufficiently low sliding speeds, the results are qualitatively similar to those with no sliding. In particular, there is always an odd number of steady-state solutions; if the steady-state is unique it is stable and if it is non-unique, stable and unstable solutions alternate, with the outlying solutions being

stable. However, we identify a sliding speed V0 above which the number of steady states is always even (including zero, implying possible non-existence of a steady-state) and again stable and unstable states alternate. A parallel numerical study shows that for V > V0 there are some initial conditions from which the contact pressure grows without limit in time, whereas for V < V0 the system will always tend to one of the stable steady states.

Ciavarella, M., Macina, G., Demelio, G.P.
On stress concentration on nearly flat contacts
(2002) Journal of Strain Analysis for Engineering Design, 37 (6), pp. 493-501. Cited 14 times.
https://www.scopus.com/inward/record.uri?eid=2-s2.0-0036864296&doi=10.1243%2f03093240232095011 6&partnerID=40&md5=61839454a29119f513b274081a09f1e4

DOI: 10.1243/030932402320950116
ABSTRACT: Fretting fatigue can severely damage components subjected to oscillatory tangential loads, leading to a dramatic reduction in fatigue life and causing catastrophic ruptures. A conservative approach that can be used when considering the effect of stress concentration induced by fretting is to ensure that the peak stress is smaller than the fatigue limit of the material. However, this depends on details of the geometry as well as loading conditions. In the present work, the contact problem of a flat rounded punch in contact with a half-plane is considered, where a dovetail joint contact geometry is approximated and the classical Hertzian contact is retrieved in the limit. Developing the analytical results given by Ciavarella, Hills and Monno, an approximate Hertzian equivalent solution using Cattaneo superposition is obtained, leading to a simple formula to estimate the maximum tangential stress as a function of the load parameter Q/(fP) and geometric parameter a/b. The accuracy of the formula is checked numerically. The proposed formula gives a maximum error as low as 4 per cent in the case of zero bulk loads. For non-zero bulk loads an analytical solution is possible for the Hertzian case for moderate bulk. This leads to a second general formula containing the three dependencies (geometry, tangential load and bulk stress), which also gives a very good approximation for rounded flat and larger bulk loads, the error being generally well below 10 per cent.

Filippi, S., Ciavarella, M., Lazzarin, P.
An approximate, analytical approach to the 'HRR'-solution for sharp V-notches
(2002) International Journal of Fracture, 117 (3), pp. 269-286. Cited 8 times.
https://www.scopus.com/inward/record.uri?eid=2-s2.0-0036820270&doi=10.1023%2fA%3a1022057621185&partnerID=40&md5=a79a0bf7781a069fa8b778f2b4fe6975

DOI: 10.1023/A:1022057621185
ABSTRACT: The well-known so-called 'HRR-solution' (Hutchinson, 1968 and Rice and Rosengren, 1968) considers the elasto-plastic stress field in a power-law strain hardening material near a sharp crack. It provides a closed form explicit expression for the stress singularity as a function of the power-law exponent 'n' of the material, but the stress angular variation functions are not found in closed form. More recently, similar formulations have appeared in the literature for sharp V-notches under mode I and II loading conditions. In such cases not only is the angular variation of the stress fields obtained numerically, but so is the singularity exponent of the stress field. In the present paper, approximate but accurate closed form solutions are first reported for sharp V-notches with an included angle greater than Π/6 radians. Such solutions, limited here to Mode I loading conditions, allow a very satisfactory estimate of the angular stress components in the neighbourhood of the notch tip, in the entire range of notch angles and for the most significant values of n (i.e. from 1 to 15). When the notch opening angle tends towards zero, and the notch approaches the crack case, the solution becomes much more complex and a precise evaluation of the parameters involved requires a best-fitting procedure which, however, can be carried out in an automatic way. This solution is also reported in the paper and its degree of accuracy is discussed in detail.

Ciavarella, M., Dini, D., Demelio, G.P.
A critical assessment of damage parameters for fretting fatigue
(2002) ASTM Special Technical Publication, (1425), pp. 108-117. Cited 1 time.
https://www.scopus.com/inward/record.uri?eid=2-s2.0-0037839773&partnerID=40&md5=1e9c316d2779b373f361224869b574c4

ABSTRACT: Fretting Fatigue (FF) has been considered as fatigue in a region of stress concentration due to the contact accelerated by mechanical erosion (possibly enhanced by metal transformations and/or chemical reactions in an aggressive environment). Whether the effect of erosion is significant or not is not clear. However, recently a more precise quantification of the effect of stress concentration has been attempted (some authors have used the terminology "crack analogue" and "notch analogue"). Most practical cases are concerned with finite stress concentration, so that a "notch analogue" criterion seems more appropriate, like for example in the Hertzian FF set of experiments like those on Aluminium alloy (Al/4%Cu, HE15-TF) by Nowell in the late '80s, and (Al2024) by Farris in late 90s. Application of the "notch analogue" with a simple stress concentration criterion is usually overconservative for a notch (and indeed it is for the experiments considered, although it may not in general because of mechanical erosion effect in the FF case), so that "averaging" methodologies have been proposed where unfortunately the best-fitting averaging constant turns to be not just a material constant. In fact, in the present paper the "best fitting distance" is shown to be much smaller than what expected from existing Kf criteria.

Ciavarella, M., Demelio, G., Schino, M., Vlassak, J.J.
The general 3D Hertzian contact problem for anisotropic materials
(2002) Key Engineering Materials, 221-222, pp. 281-292. Cited 8 times.
https://www.scopus.com/inward/record.uri?eid=2-s2.0-0036431008&partnerID=40&md5=af3ac12f3d9f53eeba17642b0640b994

ABSTRACT: This paper presents a general method for solving the 3D frictionless contact problem between generally anisotropic materials with any second order surface geometry. The method uses the Stroh formalism to find the Green's Functions (GF) of the materials with an efficient numerical integration process. The GFs are then expanded in Fourier series in order to solve the Hertzian contact problem between the two bodies as a perturbation to the first order, "equivalent isotropic", solution to the problem. The latter permits to define an "equivalent indentation modulus of the contact" which is a single parameter computed from the first terms of the Fourier expansion of the two GFs (i.e. the average values) and permits the use of standard Hertzian solution. This gives a good approximation to the contact area (at most elliptical in any case) as a circle for axi-symmetrical geometry, and an even better accuracy for other quantities such as the elastic compliance (or the inverse, elastic stiffness) of the contact. The "equivalent indentation modulus", which depends on materials and orientation, is therefore computed for a class of composite materials of practical interest.

Ciavarella, M., Decuzzi, P., Monno, G.
The design of hydrodynamically lubricated journal bearings against crack propagation
(2001) Journal of Strain Analysis for Engineering Design, 36 (2), pp. 245-250.
https://www.scopus.com/inward/record.uri?eid=2-s2.0-0035735450&doi=10.1243%2f0309324011512676&partnerID=40&md5=5df61f5cda8ed0db904948dec0461679

DOI: 10.1243/0309324011512676
ABSTRACT: Following a recently published paper, the likelihood of radial crack propagation from the surface of a hydraulically lubricated journal bearing is studied, under the hypothesis of the previous paper, i.e. assuming a half-

Sommerfeld pressure distribution in an infinitely elongated bearing. Simple results are obtained and the effect of the lubricant is estimated. A complete set of stress intensity factors is given.

Borri-Brunetto, M., Chiaia, B., Ciavarella, M.
Incipient sliding of rough surfaces in contact: A multiscale numerical analysis
(2001) Computer Methods in Applied Mechanics and Engineering, 190 (46-47), pp. 6053-6073. Cited 96 times.
https://www.scopus.com/inward/record.uri?eid=2-s2.0-0035860272&doi=10.1016%2fS0045-7825%2801%2900218-3&partnerID=40&md5=5c212cff5747abf40079cf00b768fd2c

DOI: 10.1016/S0045-7825(01)00218-3
ABSTRACT: In this paper, the Cattaneo theory of frictional contact is extended to elastic half-spaces in contact through rough disordered interfaces. The discrete version of the Cattaneo theorem is provided, and represents the basis of a multiscale numerical contact algorithm. Mathematical surfaces with imposed roughness, as well as experimentally digitised ones, are analysed. By means of a numerical method, the evolution of the contact domain, at different resolution, is investigated. Roughness of the interfaces provides lacunarity of the contact domains, whose fractal dimension is always smaller than 2.0. When a tangential force is applied, the extent of the stick area decreases in the same way as the contact area develops with increasing pressure, and the slip area is found to be proportional to the tangential force, as predicted by Cattaneo theory. The evolution of the shear centroid, as well as the amount of dissipated energy up to full-sliding, are provided. Finally, it is shown that, at a sufficient level of discretization, the distribution of contact pressures is multifractal.

Ciavarella, M., Decuzzi, P.
The state of stress induced by the plane frictionless cylindrical contact. I. The case of elastic similarity
(2001) International Journal of Solids and Structures, 38 (26-27), pp. 4507-4523. Cited 84 times.
https://www.scopus.com/inward/record.uri?eid=2-s2.0-0035872809&doi=10.1016%2fS0020-7683%2800%2900289-4&partnerID=40&md5=514211b9523a11e53afb634246157684

DOI: 10.1016/S0020-7683(00)00289-4
ABSTRACT: The contact problem between cylindrical conformal surfaces, modelling for instance a fastener joint, is studied. A closed form solution is obtained in Part I of the paper for the case of elastic similarity, improving (i) the solution obtained by Persson (On the Stress Distribution of Cylindrical Elastic Bodies in Contact, Ph.D. dissertation, 1964), which was also limited to identical materials, and (ii) the results of Noble and Hussain (Int. J. Engng. Sci. 7 (1969) 1149), which were limited to the case of perfect fit of contacting materials. The variation of the contact area, pressure distribution and maximum sustainable load is given for the complete range of possible dimensionless loading parameter Ep1*ΔR/Q and first Dundurs' material parameter, α. Under conditions of initial clearance, the contact area arc, ε, increases with load from zero to a limiting value, εlim, which depends only on the material parameter α. Vice versa, under conditions of initial interference, the contact is complete until there is detachment and the contact area starts to decrease with load up to the same limiting value, εlim, which is also the only possible value of contact area for neat-fit conditions, under any applied load. Finally, a complete assessment of the strength of the contact is given for the entire range of working conditions. As expected, the strength of the joint decreases rapidly if the extent of the contact area reduces, and finally tends to the limit predicted by the Hertzian theory when the arc of contact is smaller than about 30°. The optimal conditions for avoiding yielding are reached for a contact arc smaller than the limiting arc εlim: This means that it is not possible to reach the optimum from a configuration of initial interference.

Ciavarella, M., Decuzzi, P.
The state of stress induced by the plane frictionless cylindrical contact. II. The general case (elastic dissimilarity)
(2001) International Journal of Solids and Structures, 38 (26-27), pp. 4525-4533. Cited 53 times.

https://www.scopus.com/inward/record.uri?eid=2-s2.0-0035872677&doi=10.1016%2fS0020-7683%2800%2900290-0&partnerID=40&md5=9edce6893feecc9c722f33a1e483dedd

DOI: 10.1016/S0020-7683(00)00290-0
ABSTRACT: In Part I of the paper, the authors have studied the contact problem between a pin and an infinite plate containing a conforming hole, in the absence of friction and in the case of elastic similarity, obtaining a closed form result which generalizes the identical materials analysis of Persson (On the stress distribution of cylindrical elastic bodies in contact, Ph.D. dissertation, 1964). Here, in Part II, the general case of contacting materials is first studied numerically, finding that the effect of elastic dissimilarity (i.e. the second Dundurs' constant not being zero) is negligible for the dimensionless pressure distribution, the maximum influence being less than 2%. Vice versa, the influence on the relation between the contact area arc semi-width, ε, and the dimensionless loading parameter E1*ΔR/Q is indeed significant; however, considering as an approximate pressure distribution the one of the elastically similar case, an extremely good approximation is obtained for the general relation ε vs. E1*ΔR/Q which can now take into account of both Dundurs' elastic parameters. In particular, the limiting value for εlim, towards which the contact tends under very high loads both under initial clearance or interference (or for any load for the perfect fit limiting case) is given as a function of both Dundurs' elastic parameters, α, β as well as the load when complete contact is lost in an interference contact, εcompl. Hence, a complete assessment of the strength of the contact can be obtained directly from the results of Part I of the paper, given that for a certain contact area extension, the correct value of load is used.

Ciavarella, M., Demelio, G.
A review of analytical aspects of fretting fatigue, with extension to damage parameters, and application to dovetail joints
(2001) International Journal of Solids and Structures, 38 (10-13), pp. 1791-1811. Cited 87 times.
https://www.scopus.com/inward/record.uri?eid=2-s2.0-0035966421&doi=10.1016%2fS0020-7683%2800%2900136-0&partnerID=40&md5=75d587d6bdc27202b31a7a07439f7080

DOI: 10.1016/S0020-7683(00)00136-0
ABSTRACT: Recent advances by the authors in analytical methods for the analysis of plane fretting fatigue (FF) contact problems are described, and new consequences for FF damage are derived. Constant normal load and oscillating tangential load (the celebrated Cattaneo-Mindlin case) are considered with in-phase oscillating moderate bulk stresses, for an arbitrary spline rotated geometry and, in particular, the flat punch with rounded corners in view of application to the dovetail joints. Extremely simple, new results are found for initiation parameters such as tangential microslip and frictional energy, which have been used under certain conditions as threshold parameters for FF. Finally, it is shown that for an "almost flat" geometry, the surface damage parameters decrease, but the tensile stress concentration increases, although it becomes more localized, suggesting that for cracks eventually initiated, the likelihood of self-arrest is higher than in the equivalent Hertzian case with same loads. This seems to interpret recent experiments, although it is not clear whether the optimal geometry in terms of FF life is the perfectly flat one, or an intermediate one.

Ciavarella, M., Demelio, G.
Elastic multiscale contact of rough surfaces: Archard's model revisited and comparisons with modern fractal models
(2001) Journal of Applied Mechanics, Transactions ASME, 68 (3), pp. 496-498. Cited 53 times.
https://www.scopus.com/inward/record.uri?eid=2-s2.0-0011542283&doi=10.1115%2f1.1352016&partnerID=40&md5=8fd7a8915695e4c7190870ad405e8557

DOI: 10.1115/1.1352016

Bergamini, G., Ciavarella, M., Demelio, G.
Recent trends in structural design of ultra-light refrigerated semitrailers
(2001) Heavy Vehicle Systems, 8 (2), pp. 142-154.
https://www.scopus.com/inward/record.uri?eid=2-s2.0-0034974916&doi=10.1504%2fijhvs.2001.001157&partnerID=40&md5=3e29020373264470d6b6e2a20540e357

DOI: 10.1504/ijhvs.2001.001157
ABSTRACT: The need for weight reduction has recently motivated the use of better steels to produce lighter chassis in semitrailers lorries, and the resulting chassis are also inevitably more flexible. On the other hand, body structures are made with improved composite materials, so that the weight reduction often corresponds to an increase in rigidity. The combination of these two changes has made the chassis-body ensemble design more complex than it used to be when chassis were extremely rigid, so that there was no major interaction in their structural behaviour with the bodies, and 'beam theory' (or at most 'plate theory') was more than sufficient to design safely. Here a structural analysis using the Finite Element Method (FEM) is presented, using examples with different chassis with a particular composite material body. The distribution of loads between body and chassis and the amount of structural coupling have been determined when the stiffness of the chassis is reduced. It is found that safe ultra-light designs can be achieved only with a detailed investigation of the stresses acting on the fasteners in the fifth wheel zone. Within such limits, very high global weight reduction can be achieved, with evident advantages for the payload, and at the same time increased safety margins.

Ciavarella, M.
Conditions of yield and cyclic plasticity around inclusions
(2000) Journal of Strain Analysis for Engineering Design, 35 (1), pp. 65-70. Cited 3 times.
https://www.scopus.com/inward/record.uri?eid=2-s2.0-0033878033&doi=10.1243%2f0309324001514026&partnerID=40&md5=9c63429d33e1cbf12c2852f9e3cf4521

DOI: 10.1243/0309324001514026
ABSTRACT: In this paper the stress field in the proximity of a circular (cylindrical) inclusion is considered. The conditions for in-plane plastic flow in the matrix are examined from a classical elasticity solution obtained by Goodier. Elementary cases are considered such as remote loading ranging from pure tensile and pure shear to equibiaxial tension. For proportional loading, it is argued that the upper bound to the shakedown limit is always twice the elastic limit; therefore, within the limits of our assumptions, if the elastic stress concentration for the equivalent stress is greater than two, there is a possibility of cyclic plasticity before bulk yielding, which means that possibly an arbitrarily large plastic strain can cumulate with increasingly high risk of exhaustion of ductility and void nucleation or detachment of the interface. Consequently, conditions under which it is possible to reach twice the elastic limit before full-scale yielding are shown in the Dundurs plane representing all possible combinations of elastic parameters. Following these lines, it is shown that there is no possibility of cyclic plasticity under remote shear; there is a limited area of the Dundurs plane for tension, including the hole case; finally, in the equibiaxial limiting case, cyclic plasticity is always possible for any combination of elastic properties.

Barber, J.R., Ciavarella, M.
Contact mechanics
(2000) International Journal of Solids and Structures, 37 (1-2), pp. 29-43. Cited 166 times.
https://www.scopus.com/inward/record.uri?eid=2-s2.0-0033898029&doi=10.1016%2fS0020-7683%2899%2900075-X&partnerID=40&md5=892ce65833c542ae36be9c64e7f1924b

DOI: 10.1016/S0020-7683(99)00075-X
ABSTRACT: Contact problems are central to Solid Mechanics, because contact is the principal method of applying loads to a deformable body and the resulting stress concentration is often the most critical point in the body. Contact is characterized by unilateral inequalities, describing the physical impossibility of tensile contact tractions (except under special circumstances) and of material interpenetration. Additional inequalities and/or non-linearities are introduced when friction laws are taken into account. These complex boundary conditions can lead to problems with existence and uniqueness of quasi-static solution and to lack of convergence of numerical algorithms. In frictional problems, there can also be lack of stability, leading to stick slip motion and frictional vibrations. If the material is non-linear, the solution of contact problems is greatly complicated, but recent work has shown that indentation of a power-law material by a power law punch is self-similar, even in the presence of friction, so that the complete history of loading in such cases can be described by the (usually numerical) solution of a single problem. Real contacting surfaces are rough, leading to the concentration of contact in a cluster of microscopic actual contact areas. This affects the conduction of heat and electricity across the interface as well as the mechanical contact process. Adequate description of such systems requires a random process or statistical treatment and recent results suggest that surfaces possess fractal properties that can be used to obtain a more efficient mathematical characterization. Contact problems are very sensitive to minor profile changes in the contacting bodies and hence are also affected by thermoelastic distortion. Important applications include cases where non-uniform temperatures are associated with frictional heating or the conduction of heat across a non-uniform interface. The resulting coupled thermomechanical problem can be unstable, leading to a rich range of physical phenomena. Other recent developments are also briefly surveyed, including examples of anisotropic materials, elastodynamic problems and fretting fatigue.

Ciavarella, M., Demelio, G.
On the extraction of notch stress intensity factors by the post-processing of stress data on the free edges of the notch
(2000) Journal of Strain Analysis for Engineering Design, 35 (3), pp. 221-226.
https://www.scopus.com/inward/record.uri?eid=2-s2.0-0033704905&doi=10.1243%2f0309324001514369&partnerID=40&md5=9a5830937bd99119318a024a9e1cdccf

DOI: 10.1243/0309324001514369
ABSTRACT: Following on the lines of a previous paper dedicated to cracked components by Ciavarella et al., here the case of a notch of semi-angle α is considered. Contrary to the crack case (α = 180°), the free edges of the notch are easily accessible to experimental analysis; moreover they provide information about all the terms of the Williams series expansion of the stress field about the notch apex, including the most important, i.e. the symmetric and antisymmetric singular term notch stress intensity factors (N-SIFs), whereas for the crack case the mode I N-SIFs cannot be extracted from those stresses. Another important different feature is that symmetric and antisymmetric N-SIFs have different singularities, and in several cases they are so close that their contributions tend to overlap. Therefore, a simple procedure is here proposed to use radial stresses, to separate their symmetric and antisymmetric contributions a priori by computing the sum and difference of the stresses on the two edges, to post-process these quantities in the `asymptotic region' with standard least-squares techniques and to extract the N-SIFs. The method is applied to a simple case known in the literature and solved by means of a boundary element code, and the results are almost coincident with previous results, even with quite coarse mesh discretizations.

Ciavarella, M., Decuzzi, P., Monno, G.
Frictionally-excited thermoelastic contact of rough surfaces
(2000) International Journal of Mechanical Sciences, 42 (7), pp. 1307-1325. Cited 6 times.

https://www.scopus.com/inward/record.uri?eid=2-s2.0-0033907758&doi=10.1016%2fS0020-7403%2899%2900051-X&partnerID=40&md5=ced3d309cd46d535d172d155a51eb83a

DOI: 10.1016/S0020-7403(99)00051-X
ABSTRACT: Frictional sliding contact between two elastically similar half-planes, one of which has a sinusoidally wavy surface, is studied in the full-contact regime. The steady-state regime is evaluated, within the limits imposed by the well-known phenomenon of thermo-elastic instability (TEI). TEI gives a critical speed whose value depends on the wavelength of the perturbation, and above which the perturbation itself grows arbitrarily with time. It is found that the TEI critical speed, Vcr, is clearly identified by the steady-state solution only in the special and limiting case when the flat half-plane is non-conductor; in that case, Vcr, is the speed for which the steady-state predicts infinite amplification. In all other cases, Vcr (appropriate to the wavelength of the profile) does not correspond to infinite amplification, nor to the maximum one, VM. In the limiting case of thermoelastically similar materials, not only the system is unconditionally stable (Vcr = ∞) for fH1 < 0.5, where f is the friction coefficient and H1 a certain thermoelastic constant, but the regime at the maximum amplification is also always stable, and arbitrarily large amplification is obtained for fH1 tending to infinity. However, it is found that in most practical cases of braking systems, Vcr ≪ VM, and so the limiting conditions are reached at Vcr. At this speed, the amplification is typically not extremely high.

Ciavarella, M., Demelio, G., Hills, D.A.
Analysis of rotating bending fretting fatigue tests using bridge specimens
(2000) ASTM Special Technical Publication, (1367), pp. 404-422. Cited 4 times.
https://www.scopus.com/inward/record.uri?eid=2-s2.0-0033874750&partnerID=40&md5=afb97056da8d016e469cb14f141bbc8c

ABSTRACT: The rotating-bending type of fretting fatigue apparatus is analyzed by treating the `feet' of the bridge as flat pads with rounded corners. This permits a closed-form solution for the contact pressure - indeed, even more complex geometries could be considered, providing the corners are not sharp - and stick/slip zones to be found, allowing for: (a) shearing force, (b) tension within the specimen and (c) tilting of the specimen with respect to the bridge. Example solutions for each of these separate effects are displayed, together with certain combinations of effects.

Ciavarella, M.
Indentation by nominally flat or conical indenters with rounded corners
(1999) International Journal of Solids and Structures, 36 (27), pp. 4149-4181. Cited 54 times.
https://www.scopus.com/inward/record.uri?eid=2-s2.0-0032636491&doi=10.1016%2fS0020-7683%2898%2900186-3&partnerID=40&md5=bc95cb081ef0744a5d49727cdf43644b

DOI: 10.1016/S0020-7683(98)00186-3
ABSTRACT: Axisymmetric indentation of a flat surface is considered: specifically, the case of flat-ended indenter with rounded edges, and the case of a shallow cone with a rounded tip. Analytical solutions are obtained for the normal and sequential tangential loading, in both full or partial slip conditions (with the Cattaneodegree polynomial in x and y. The most relevant are Hertzian elliptical contacts (as proved explicitly by) and plane problems (,) . Indeed, for plane problems, with no dependence, say, on y, ΔV (x) = (d 2V (x) /dx2) = h1+h2 has a general solution V (x) = [(h1+h2) /2] x2+c. Other particular cases of such exact solutions may exist, with a more general shape of stick area, but the question of limited practical interest, as long as the surface profiles to produce that contact area and symmetry are of rather particular form, so that the property will hold only for very special values of geometry and load.Mindlin approximation) , and for the complete interior stress field in all these conditions. Implications for strength of the contact are discussed with reference to metallic or brittle materials, with the

intention to shed more light in particular to the understanding of common fretting fatigue or indentation testings with nominally flat or conical indenters. It is found that the strength of the contact, which is nominally zero for perfectly sharp flat or conical indenters, is well defined even for a small radius of curvature. This is particularly true for the flat indenter, for which the strength is even significantly higher than for the classical Hertzian indenter for a wide range of geometrical and loading conditions, rendering it very attractive for design purposes.

Ciavarella, M., Demelio, G.
Numerical methods for the optimisation of specific sliding, stress concentration and fatigue life of gears
(1999) International Journal of Fatigue, 21 (5), pp. 465-474. Cited 28 times.
https://www.scopus.com/inward/record.uri?eid=2-s2.0-0345534595&doi=10.1016%2fS0142-1123%2898%2900089-9&partnerID=40&md5=f542c8f9133e810d48639dc94b9bdc1b

DOI: 10.1016/S0142-1123(98)00089-9
ABSTRACT: Presented in this paper is a set of modern tools for the design of gearing: kinematic optimisation (minimisation and balancing of specific sliding), static stress analysis (to minimise stress concentrations) and crack propagation studies (to estimate fatigue life under a pre-existing defect). All three aspects are integrated in a software package developed by the authors. In particular, Boundary Element (BE) and Finite Element (FE) grids are automatically generated corresponding to gears manufactured by means of user defined tools with known shape and cutting parameters. BE models are used for a complete and automatic subcritical propagation analysis of cracks. FE models are used mostly for cases without crack propagation but requiring a greater versatility. Tests conducted on cases found in the literature demonstrate the accuracy of the methods used and the effects of rack shift factors and of rim thickness are studied in example cases. It is found that the fatigue life depends significantly on the cracking path mode, which in turn is particularly sensitive to the rim thickness in gears manufactured on thin hollow shafts as are typical in aeronautical applications. Further, the rack shift factors significantly change the stress concentrations (and therefore the maximum torque transmittable, in general in a beneficial manner). However, for designs with same concentration factor the fatigue life is considerably different and in particular is lower on gears with a low number of teeth. This clearly indicates that the use of a complete crack propagation analysis from the early stages of the design process is highly recommended.

Ciavarella, M., Hills, D.A.
The influence of the indenter tip-radius on indentation testing of brittle materials
(1999) Journal of the European Ceramic Society, 19 (2), pp. 239-245. Cited 6 times.
https://www.scopus.com/inward/record.uri?eid=2-s2.0-0033079444&doi=10.1016%2fS0955-2219%2898%2900188-5&partnerID=40&md5=ab212560b61813de57d847e9451d797e

DOI: 10.1016/S0955-2219(98)00188-5
ABSTRACT: Indentation testing of a brittle material using a notionally 'sharp' indenter may reveal several important physical properties, including fracture toughness, surface finish information and the residual stress state. In the case of shallow cone indenters, the contact and fracture mechanics is well defined and closed-form solutions exist in elasticity theory. However, no real indenter is atomically sharp, and the scope of the present article is to quantify how a finite apex radius may modify the stress state induced by a conical indenter. In particular, implications for the load-displacement relation, occurrence of yielding and maximum contact pressure induced are found. A brief discussion of the influence of edge radius on the flat-ended indenter, once used to induce Hertzian type ring cracks, is also included, as this may be treated by a similar procedure.

Ciavarella, M., Demelio, G.
On non-symmetrical plane contacts
(1999) International Journal of Mechanical Sciences, 41 (12), pp. 1533-1550. Cited 24 times.

https://www.scopus.com/inward/record.uri?eid=2-s2.0-0032652297&doi=10.1016%2fS0020-7403%2898%2900105-2&partnerID=40&md5=68b75bb1b84d851c9c7ef79d19c24fa0

DOI: 10.1016/S0020-7403(98)00105-2
ABSTRACT: Plane elastic contact problems are considered, with particular emphasis on asymmetrical punch profiles, in the case of `complete', `partially complete' and `incomplete' contact. An explicit, analytical solution is presented for the case of a single area of contact where the overlap is described by a generic spline function, and examples presented. The interior stress field and strength of the contact, under full or partial slip conditions, are also discussed, and some example shown for representative cases. It is found also that the direction of sliding has a significant effect for the strength of non-symmetrical contacts.

Ciavarella, M., Hills, D.A.
Brief note: some observations on oscillating tangential forces and wear in general plane contacts
(1999) European Journal of Mechanics, A/Solids, 18 (3), pp. 491-497. Cited 42 times.
https://www.scopus.com/inward/record.uri?eid=2-s2.0-0032598332&doi=10.1016%2fS0997-7538%2899%2900117-5&partnerID=40&md5=f8108ca39adc85078656c645827e5733

DOI: 10.1016/S0997-7538(99)00117-5
ABSTRACT: For general plane contact of elastically similar materials, including cases where there are multiple regions of contact, general properties of the partial slip solution for conditions of constant normal force and monotonically increasing shearing force have been found recently by the first author. An extension is given here to cover the unloading and cyclic loading cases. Further, it is shown that, if the tangential load varies between two fixed limits, the region of stick does not change, even if relative microslip causes wear, changing continuously the profile of the indenter. The contact area will change, but wear will not enter the original region of adhesion. The theoretical limit to which wear will eventually, asymptotically proceed is established, viz. almost complete contact over what is the initial stick zone, although it may, in practice, take a long time to reach this state.

Ciavarella, M., Hills, D.A.
Note on convective effects in elastic contact problems for dissimilar materials
(1999) European Journal of Mechanics, A/Solids, 18 (3), pp. 481-490. Cited 3 times.
https://www.scopus.com/inward/record.uri?eid=2-s2.0-0032598328&doi=10.1016%2fS0997-7538%2899%2900115-1&partnerID=40&md5=4b2391e668eb2767e3a25d1c151db1ed

DOI: 10.1016/S0997-7538(99)00115-1
ABSTRACT: In this paper we discuss the effect of neglecting relative tangential surface displacements in forming the boundary conditions of elastic contact problems between dissimilar materials. This is one of the known approximations made by Hertz in his original theory. Attempts have been made only recently to build up procedures to take this 'convective' effect into account, for simple plane problems (Soldatenkov, 1996). However, before questioning all the existing solutions for elastically dissimilar contact problems, it is considered important to estimate quantitatively the order of the possible correction. Here a simple iterative procedure is set up to solve frictionless plane contact problems taking into account the 'convective effect'. Attention is focused on the problem of wedge indentation, as this provides a reasonably tractable problem, and on the parabolic indenter, to discuss the Hertzian case. The correction introduced is shown not to be negligible, but is of practical significance only in extreme conditions, viz. frictionless contact and large Dundurs' constant, β. In these extreme cases, the maximum correction to the contact are dimension may be of the order of an increase of 10% for the contact area dimension. The effect tends to be more significant for Hertzian indenter and higher order profiles.

Ciavarella, M., Hills, D.A., Moobola, R.

Analysis of plane and rough contacts, subject to a shearing force
(1999) International Journal of Mechanical Sciences, 41 (1), pp. 107-120. Cited 20 times.
https://www.scopus.com/inward/record.uri?eid=2-s2.0-0032761419&doi=10.1016%2fS0020-7403%2898%2900038-1&partnerID=40&md5=d536e5f6c3db6e9d44ca7513e2dc5385

DOI: 10.1016/S0020-7403(98)00038-1
ABSTRACT: We analyse the surface traction conditions induced in plane contact between two bodies whose surfaces are rough. It is assumed that the roughness may be idealised by a surface of regularly spaced cylindrical "bumps", and the overall geometry may be in the form of a cylinder, flat ended punch or wedge. The stick-slip regime experienced by each individual asperity contact is found, and hence it is shown how the applied shearing force produces concentrated regions of surface damage. Conditions for crack initiation are then discussed, and compared with equivalent results found for nominally smooth contacts.

Ciavarella, M., Demelio, G., Hills, D.A.
Use of almost complete contacts for fretting fatigue tests
(1999) ASTM Special Technical Publication, (1332), pp. 696-709. Cited 5 times.
https://www.scopus.com/inward/record.uri?eid=2-s2.0-0032674606&doi=10.1520%2fstp14978s&partnerID=40&md5=19c4e1e7c9dd57061fafc30145ec6ed3

DOI: 10.1520/stp14978s
ABSTRACT: In this paper we analyse the frequently used bridge-type fretting fatigue tests, by idealizing the specimens as having almost-flat-ended feet, but with small blend radii. An estimate of the shearing force developed is given, and the relevant partial slip contact problem is solved. We then go on to examine further characteristics of the problem such as the local density of energy expenditure against friction, and the crack tip stress intensity factors found for cracks.

Ciavarella, M., Decuzzi, P., Demelio, G., Monno, G., Hills, D.A.
Design of hydrodynamically lubricated journal bearings against yield
(1999) Journal of Strain Analysis for Engineering Design, 34 (3), pp. 165-173. Cited 3 times.
https://www.scopus.com/inward/record.uri?eid=2-s2.0-0032623724&doi=10.1243%2f0309324991513722&partnerID=40&md5=faa89712ec3a77bda0fe0749fd782dfd

DOI: 10.1243/0309324991513722
ABSTRACT: The stress field induced by the half-Sommerfeld pressure distribution in an infinitely elongated bearing is studied in detail. A complex potential formulation for the stress field is employed to solve the elasticity problem, with the intention to compute the required strength according to the classical von Mises criterion. Example contour plots of the yield parameter (√J2)/pm are given and the position and magnitude of the maximum normalized von Mises parameter are determined for a range of working conditions, analytically when they are on the surface, i.e. for eccentricity ratios ε<0.6, and semi-analytically for the cases where they are located subsurface, i.e. ε>0.6. Surprisingly simple results are obtained for eccentricity ratios lower than about 0.7, namely a maximum of the von Mises parameter proportional to the mean pressure, permitting a simple rule to be developed for the design of bearings against yielding: if the bearing works with eccentricity ratios smaller than 0.7, and the average pressure is smaller than 1.22k, where k is the yield stress of the material in pure shear, then yielding is avoided. When bearings are used in the range of very high eccentricity ratios, a more refined calculation is needed, taking into account the actual value of the maximum von Mises parameter and the paper provides design charts for this purpose.

Ciavarella, M., Hills, D.A., Monno, G.
Contact problems for a wedge with rounded apex
(1998) International Journal of Mechanical Sciences, 40 (10), pp. 977-988. Cited 36 times.
https://www.scopus.com/inward/record.uri?eid=2-s2.0-0032187633&doi=10.1016%2fS0020-7403%2897%2900141-0&partnerID=40&md5=6b4df055e5af7d42f136215b994d72c2

DOI: 10.1016/S0020-7403(97)00141-0
ABSTRACT: Elastic contact between a shallow elastic wedge, whose apex is blunted by a finite radius, and an elastically similar half-plane is studied. A closed-form contact law is found, and the interior stress field is then deduced using a Muskhelishvili's solution in series form, for frictionless and sliding conditions. This geometry removes one of the principal objections to classical solutions to the wedge indentation problem - the unrealistic infinite stress concentration implied by an atomically sharp apex - and in the latter part of the paper the strength of the contact is evaluated explicitly. Further, cases of partial slip associated with the application of tangential load less than needed to cause sliding are considered.

Ciavarella, M.
The generalized cattaneo partial slip plane contact problem. I - Theory
(1998) International Journal of Solids and Structures, 35 (18), pp. 2349-2362. Cited 179 times.
https://www.scopus.com/inward/record.uri?eid=2-s2.0-0032083723&doi=10.1016%2fS0020-7683%2897%2900154-6&partnerID=40&md5=c8ca20236fc2e4585778953c4710ba08

DOI: 10.1016/S0020-7683(97)00154-6
ABSTRACT: The Cattaneo problem is considered for a general plane contact between elastically similar materials, i.e. a monotonically increasing tangential load, starting from zero, with normal loading held fixed. Instead of the classical argument on the displacement field in the stick zone of Cattaneo solution, we attack the problem implicitly from the governing integral equations in the stick zones. After discussing and solving the full-stick case, we move to the more realistic (for finite friction) case of partial slip. We show that, upon isolating the effect of full sliding, the equalities and inequalities governing the corrective solution for the corrective shearing tractions in the stick zone are exactly the same as those governing the solution of the normal contact problem with a lower load, but the same rotation as the actual one. This analogy permits us to deduce several general properties, and gives a general procedures for solving partial slip Cattaneo problems as frictionless normal indentation ones. Therefore, the general solutions for single, multiple and periodic contacts is given. A comprehensive set of explicit results is given in the part II of the paper.

Ciavarella, M.
The generalized cattaneo partial slip plane contact problem. II - Examples
(1998) International Journal of Solids and Structures, 35 (18), pp. 2363-2378. Cited 66 times.
https://www.scopus.com/inward/record.uri?eid=2-s2.0-0032083686&doi=10.1016%2fS0020-7683%2897%2900155-8&partnerID=40&md5=0de63412e7a74df637ccc095c540491b

DOI: 10.1016/S0020-7683(97)00155-8
ABSTRACT: This second part of the paper uses the method devised in the part 1 to give explicit solution to several cases of Cattaneo's plane contact problem, where a monotonically increasing tangential load, starting from zero, is applied to the bodies in contact, with normal loading held fixed. The method consists in reducing the partial slip problem to a superposition of frictionless normal contact problems, for which several results are available, including some recent cases studied by the author. Therefore, a comprehensive set of results is given for single, multiple and periodical contacts.

Ciavarella, M.
Tangential loading of general three-dimensional contacts
(1998) Journal of Applied Mechanics, Transactions ASME, 65 (4), pp. 998-1003. Cited 46 times.
https://www.scopus.com/inward/record.uri?eid=2-s2.0-0001152963&doi=10.1115%2f1.2791944&partnerID=40&md5=06ed6f4b5e3f891f7b1eb2e757fc66c4

DOI: 10.1115/1.2791944
ABSTRACT: A general three-dimensional contact, between elastically similar half-spaces, is considered. With a fixed normal load, we consider a pure relative tangential translation between the two bodies. We show that, for the case of negligible Poisson's ratio, an exact solution is given by a single component of shearing traction, in the direction of loading. It is well known that, for full sliding conditions, the tangential force must be applied through the center of the pressure distribution. Instead, for a full stick case the tangential force must be applied through the center of the pressure distribution under a rigid flat indenter whose planform is the contact area of the problem under consideration. Finally, for finite friction a partial slip regime has to be introduced. It is shown that this problem corresponds to a difference between the actual normal contact problem, and a corrective problem corresponding to a lower load, but with same rotation of the actual normal indentation. Therefore for a pure translation to occur in the partial slip regime, the point of application of the tangential load must follow the center of the "difference" pressure. The latter also provides a complete solution of the partial slip problem. In particular, the general solution in quadrature is given for the axisymmetric case, where it is also possible to take into account of the effect of Poisson's ratio, as shown in the Appendix. © 1998 by ASME.

Ciavarella, M., Hills, D.A., Monno, G.
The influence of rounded edges on indentation by a flat punch
(1998) Proceedings of the Institution of Mechanical Engineers, Part C: Journal of Mechanical Engineering Science, 212 (4), pp. 319-327. Cited 146 times.
https://www.scopus.com/inward/record.uri?eid=2-s2.0-0031699271&doi=10.1243%2f0954406981521259&partnerID=40&md5=8509db48dccff9f95c8021e3724aed25

DOI: 10.1243/0954406981521259
ABSTRACT: The contact problem and stress state for indentation by a flat punch with rounded edges is studied. For the contact problem itself analytical solutions are obtained for both surface pressure and interior stress fields. Cases of normal indentation and frictional contact, the latter in both sliding or partial slip conditions, are all treated. The transition from the Hertzian configuration to the contact between a nominally flat pad and contacting flat surface is discussed, and it is found that the strength of the contact decays surprisingly slowly. Regarding the von Mises yield parameter, there is a range of configurations for which the strength is actually higher than the Hertzian one, and the strength decays only when the corner radii are very small. The present solution is therefore a realistic alternative to the classical rigid-flat punch idealization, and has particular application to fretting fatigue tests. © IMechE 1998.

Ciavarella, M., Demelio, G., Pappalettere, C.
On the post-processing of data obtained from cracked components
(1998) Journal of Strain Analysis for Engineering Design, 33 (1), pp. 67-70. Cited 1 time.
https://www.scopus.com/inward/record.uri?eid=2-s2.0-0031649410&doi=10.1243%2f0309324981512823&partnerID=40&md5=b63611a2671af0a4efb6ec80bfbd89f1

DOI: 10.1243/0309324981512823
ABSTRACT: The use of a simple singular value decomposition (SVD) technique to post-process far-field data from cracked components is discussed. The technique employs the series expansion for stress or displacements ahead

of the crack tip, which is available for a wide range of configurations. The use of higher-order terms necessary for the post-processing, is beneficial for two reasons: (a) it permits the abstraction of the maximum usable amount of information; (b) it gives a better understanding of the fracture mechanics especially regarding crack tip plasticity and dynamic propagation. Several numerical cases are examined and a comparison is made with analytical results, permitting an evaluation to be made of the pure numerical error in the post-processing.

Ciavarella, M., Demelio, G., Monno, G., Hills, D.A.
The influence of specimen size on the surface stress distribution induced by indentation testing
(1997) Journal of the European Ceramic Society, 17 (14), pp. 1691-1696.
https://www.scopus.com/inward/record.uri?eid=2-s2.0-0031383587&doi=10.1016%2fS0955-2219%2897%2900039-3&partnerID=40&md5=d2ab500872deda240355d45f4d264800

DOI: 10.1016/S0955-2219(97)00039-3
ABSTRACT: The stress state in an elastic cylindrical coupon of finite dimensions on a rigid, frictionless foundation under axisymmetric contact loading is studied. The axisymmetric stress analysis is devoted to an investigation of the effects of the free surfaces of the plate on the surface radial tensile stress field, which is particularly important for an assessment of crack initiation in brittle materials. Attention is focused on cases where the ratio of plate thickness (h) and plate radius (w) to contact radius (a) fall in the range 0·5 < h/a < 10, and 1 < w/a < 5, respectively, which is the region of both experimental and theoretical interest.