



UvA-DARE (Digital Academic Repository)

Sliding friction

From microscopic contacts to Amontons' law

Weber, B.A.

Publication date

2017

Document Version

Other version

License

Other

[Link to publication](#)

Citation for published version (APA):

Weber, B. A. (2017). *Sliding friction: From microscopic contacts to Amontons' law*.

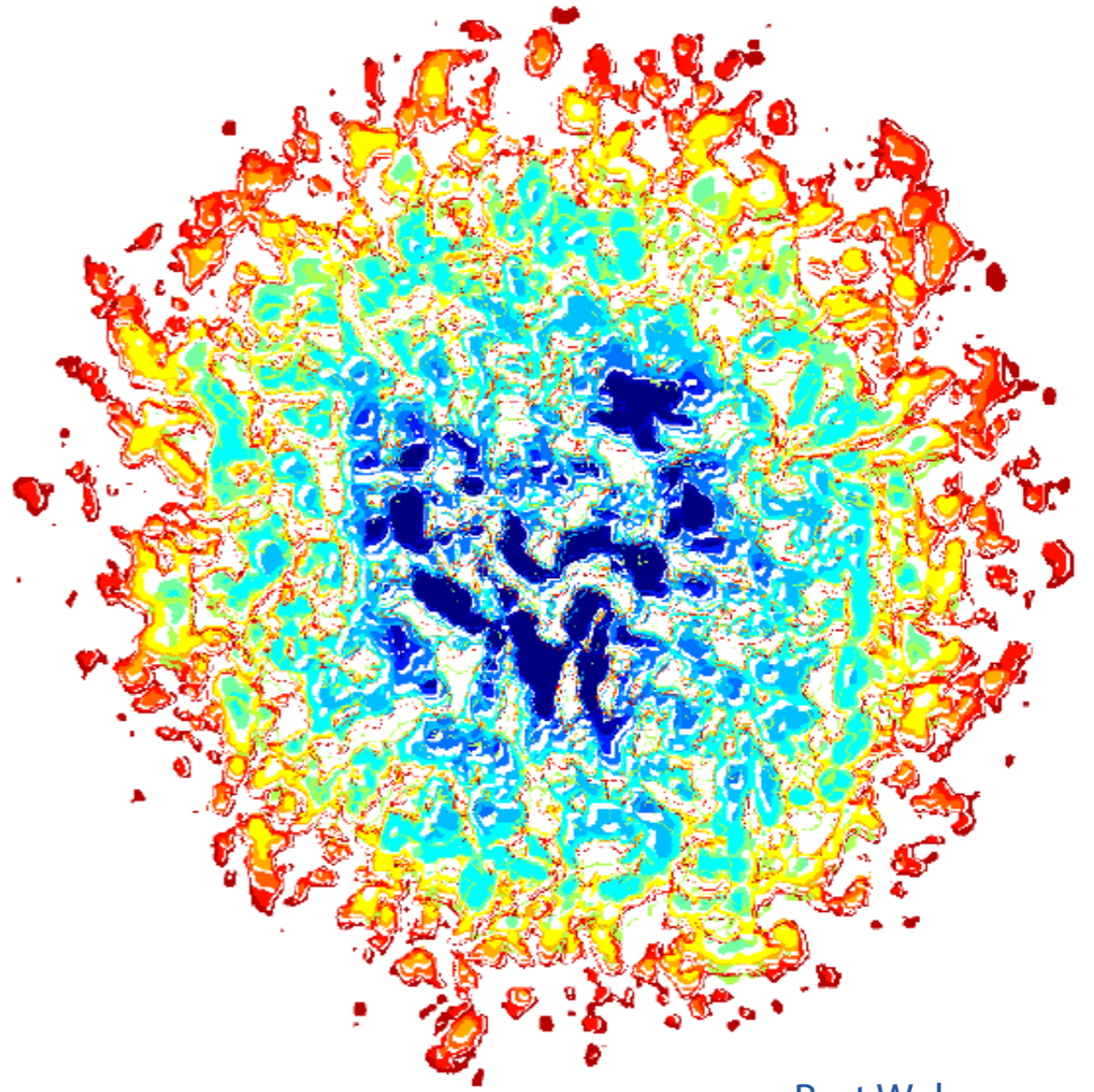
General rights

It is not permitted to download or to forward/distribute the text or part of it without the consent of the author(s) and/or copyright holder(s), other than for strictly personal, individual use, unless the work is under an open content license (like Creative Commons).

Disclaimer/Complaints regulations

If you believe that digital publication of certain material infringes any of your rights or (privacy) interests, please let the Library know, stating your reasons. In case of a legitimate complaint, the Library will make the material inaccessible and/or remove it from the website. Please Ask the Library: <https://uba.uva.nl/en/contact>, or a letter to: Library of the University of Amsterdam, Secretariat, Singel 425, 1012 WP Amsterdam, The Netherlands. You will be contacted as soon as possible.

Sliding Friction: From Microscopic Contacts to Amontons' Law



Bart Weber

Sliding Friction: From Microscopic Contacts to Amontons' Law

Bart Weber

**Sliding Friction: From
Microscopic Contacts to
Amontons' Law**

Bart Weber

Sliding Friction: From Microscopic Contacts to Amontons' Law

ACADEMISCH PROEFSCHRIFT

ter verkrijging van de graad van doctor
aan de Universiteit van Amsterdam
op gezag van de Rector Magnificus
prof. dr. ir. K.I.J. Maex
ten overstaan van een door het College voor Promoties
ingestelde commissie,
in het openbaar te verdedigen in de Agnietenkapel
op woensdag 4 oktober 2017, te 14:00 uur

door

Bart Alexander Weber

geboren te Amsterdam

Promotiecommissie

Promotor: Prof. dr. D. Bonn Universiteit van Amsterdam

Copromotor: Prof. dr. A.M. Brouwer Universiteit van Amsterdam

Overige leden: Prof. dr. H. Bakker Universiteit van Amsterdam

Prof. dr. J. Fineberg The Hebrew University of Jerusalem

Prof. dr. J.W.M. Frenken Universiteit van Amsterdam

Prof. dr. J.F. Molinari École Polytechnique Fédérale de Lausanne

Prof. dr. L. Pastewka University of Freiburg

Prof. dr. S. Woutersen Universiteit van Amsterdam

Faculteit der Natuurwetenschappen, Wiskunde en Informatica

The work reported in this thesis was carried out at the Van der Waals-Zeeman Institute, IoP, University of Amsterdam. This work is part of the research programme 'Fundamental Aspects of Friction' of the Foundation for Fundamental Research on Matter (FOM), which is part of the Netherlands Organisation for Scientific Research (NWO)



Netherlands Organisation
for Scientific Research

Contents

1	Introduction	1
2	Experimental Techniques	9
2.1	Elastic modulus	9
2.1.1	Shear modulus of wet sand	9
2.1.2	Young's modulus of polytetrafluoroethylene	11
2.2	Penetration hardness	13
2.3	Friction tests	15
2.3.1	Friction experiments with a tensile tester	16
2.3.2	Friction experiments with a rheometer	17
	Full rotations	18
2.4	Microscopy imaging	19
2.4.1	Fluorescence microscopy	20
2.4.2	Atomic force microscopy	23
3	Sliding Friction on Wet and Dry Sand	27
3.1	Abstract	27
3.2	Introduction	27
3.3	Experiment	28
3.4	Results	30
3.5	Conclusion	34
4	Fluorescence Microscopy Visualization of Contacts Between Objects	39
4.1	Abstract	39
4.2	Introduction	39
4.3	Experiment	40
4.4	Results	43
4.5	Conclusion	45

5	Molecular Probes Reveal Deviations from Amontons' Law in Multi-Asperity Frictional Contacts	55
5.1	Abstract	55
5.2	Introduction	56
5.3	Experiment	56
5.4	Results	57
5.5	Conclusion	62
6	The Onset of Sliding Friction	69
6.1	Abstract	69
6.2	Introduction	69
6.3	Experiment	70
6.4	Results	72
6.5	Conclusion	77
7	Molecular Insight into the Slipperiness of Ice	81
7.1	Abstract	81
7.2	Introduction	81
7.3	Results	82
7.4	Conclusion	89
	Appendices	95
A	Fluorescence Microscopy Visualization of Contacts Between Objects	97
B	Molecular Probes Reveal Deviations from Amontons' Law in Multi-Asperity Frictional Contacts	101
B.1	Experimental methods	101
B.1.1	Microscopy	101
B.1.2	Mechanical testing	108
Roughening	108	
Elastic modulus	108	
Friction	109	
B.2	Numerical contact models	109
B.2.1	Greenwood & Tripp model	109
B.2.2	Elastic interactions	109
B.2.3	Plasticity models	110
B.2.4	Comparison with experiments	111
B.3	Other materials	113

C Molecular Insight into the Slipperiness of Ice	121
C.1 Friction on different ice surfaces	121
C.2 Normal force dependence	121
C.3 Ploughing force	123
C.4 Indentation experiments	123
C.5 Friction and contact area	125
C.6 Frictional heating	125
C.7 Sum-frequency generation spectroscopy	128
C.8 Simulation protocols	128
C.8.1 Molecular dynamics simulation	128
C.8.2 SFG spectra calculation	129
C.8.3 Definition of free O-H group of water	130
Summary	135
Samenvatting	139
List of Publications	143
Acknowledgements	145