Micromechanical modeling of the contact behavior of fine adhesive particles

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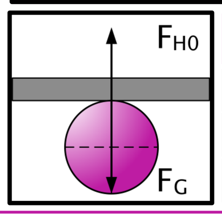
1. Macroscopic Process and handling problems of fine, cohesive powders (d<100 µm)

Product design | Conveying | Transport | Packing

→ Flow properties

2. Decreasing particle size: the interparticular adhesion forces, especially van der Waals attraction forces exceed the weight forces



Particle size d in µm	Ratio $F_{VdW\ Adhesion\ force} / F_{weight\ force}$
10 – 100	1 – 100
1 – 10	100 – 10^4
0.01 – 1	10^4 – 10^8

Problem Definition

Central Aim: Understanding of the physical properties by

- ✓ Approach
- ✓ Contact
- ✓ Detachment

} Fine, dry and adhesive particles

Objectives

(1) Implementation of new contact models and simulation (PFC^{3D})

(2) Measurement of micromechanical properties (AFM, Nanoindentation, Compression tests)

(3) Macromechanical shear cell experiments

(4) Evaluation of the process (experiments – simulations)

Cooperation

Z. Kutelova – University Magdeburg
Production and modification of particles

S. Aman – University Magdeburg:
Compression tests

L. te Kamp – Itasca:
DEM – Simulations

Characterization of particle systems / Modeling & Simulation

T. Staedler – University Siegen:
Nanoindentation

M. Kappl – MPI Mainz:
Adhesion force experiments (AFM)

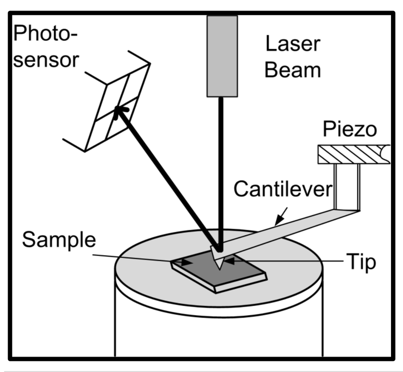
S. Luding – University Twente:
Comparison and calibration of contact models

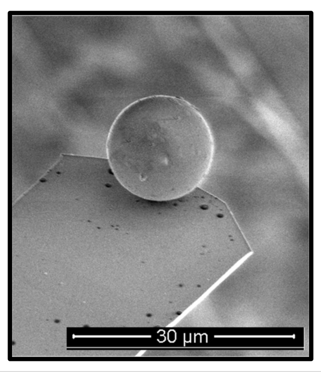
Experimental Setup

Direct adhesion force measurement

1) Atomic force microscopy

Principle





Sample preparation

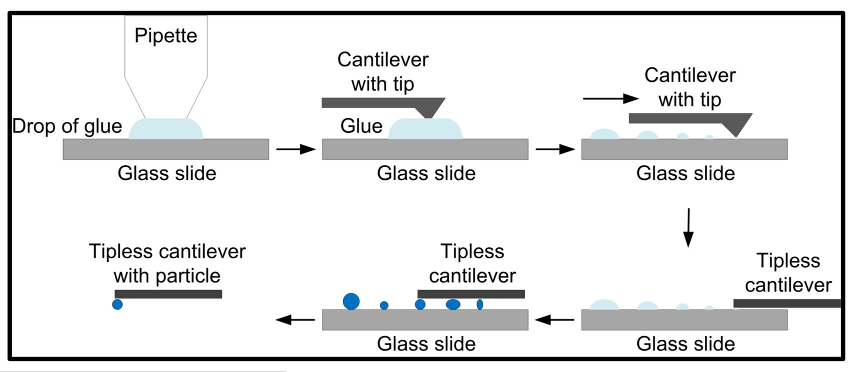
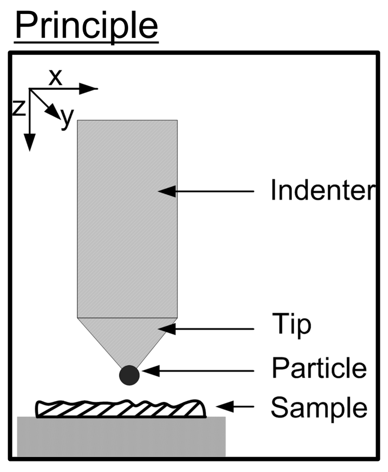


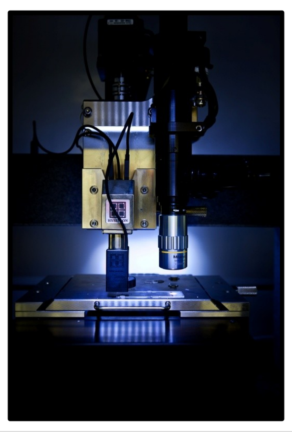
Figure 1. Asylum Research MFP 3DTM at University Siegen

Model-based back-calculation

2) Nanoindentation

Principle





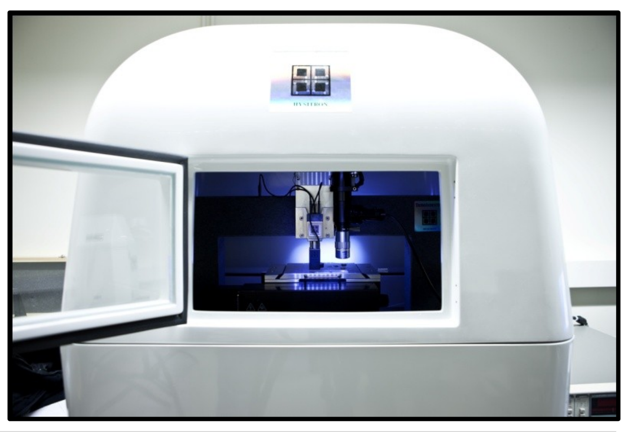


Figure 2. TriboIndenter (Hysitron Inc.) at University Siegen

Sample preparation:

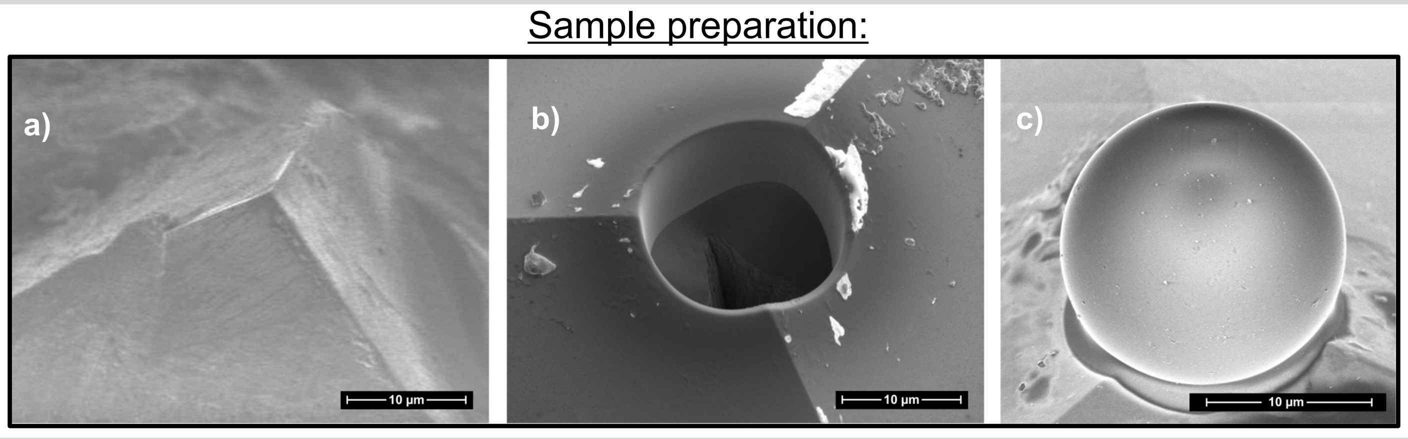


Figure 3. a) Three-sided pyramidal diamond cube corner tip (Hysitron Inc.); b) Cut hole using focused ion beam (FIB Helios Nanolab 600 at University Siegen); c) Fixed glass particle (adhesive: DIC Europe GmbH)

3) Compression tests

Principle

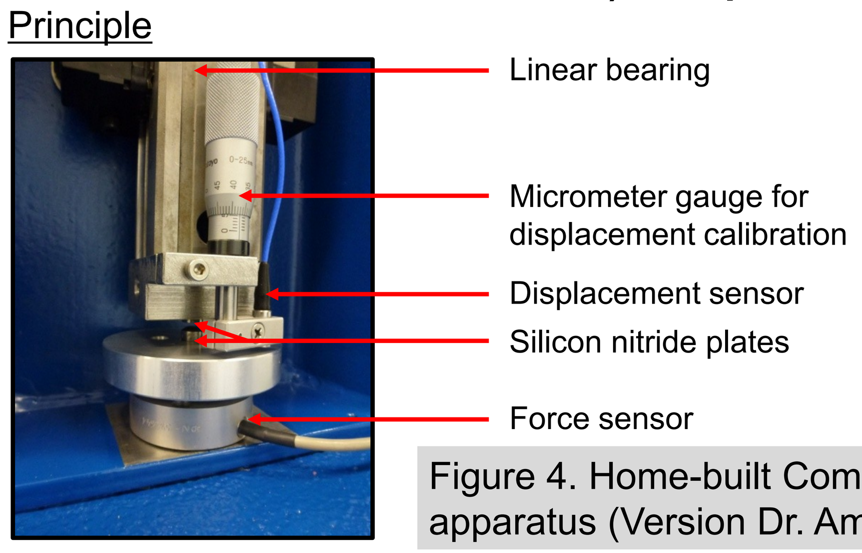
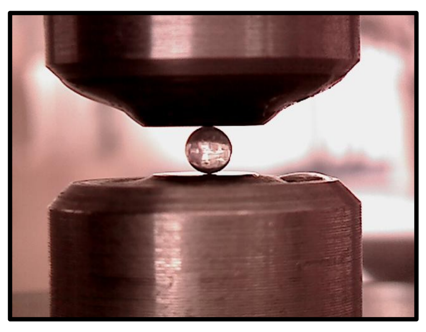


Figure 4. Home-built Compression apparatus (Version Dr. Aman)

Sample preparation:



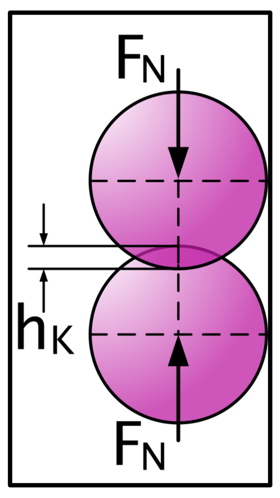
Glass particle between two silicon nitride plates ($d_{particle}$ = 5 mm)

Analytical Description

Model ‚stiff particles with soft contacts'

- ✓ External forces and short-range adhesion forces (near surface) generate directly a localized contact deformation
- ✓ Contact area is small in comparison to the sphere cross section
- ✓ Neglecting of the particle deformations outside of the contact
- ✓ Particle contact with variable adhesion
- ✓ Adhesive, elastic-plastic, viscoelastic and viscoelastic-plastic contact deformation

Normal loading for two spherical particles:



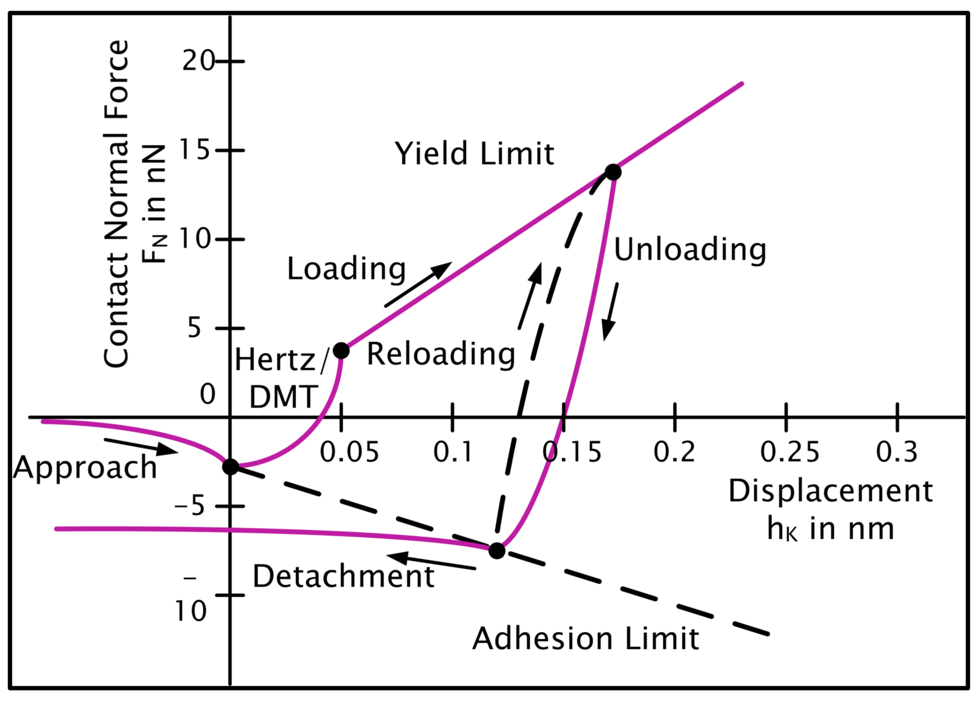


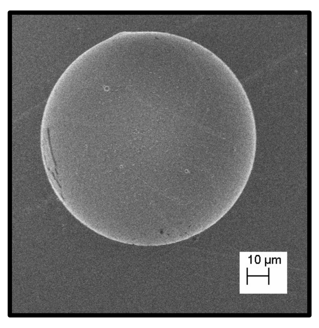
Figure 5. Characteristic normal force-displacement behavior of two smooth isotropic particles

Reference particle system

Correlation between the contact model and the physical material properties

Glass particles

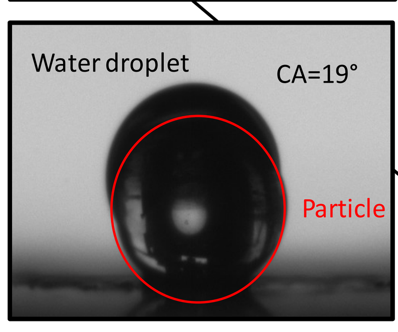
- ✓ Ideal spheres
- ✓ Ratio F_{H0}/F_G: $1.3 \cdot 10^3$ > adhesive
- ✓ Contact consolidation coefficient κ: 0.1 > stiff



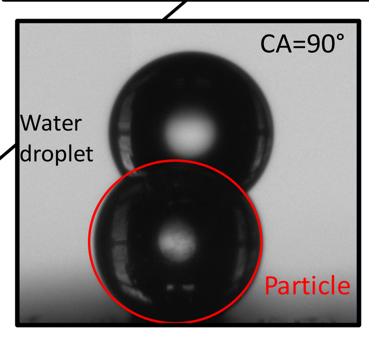
Material Data	Glass
Particle size d_{50} in µm	5.8
Particle mass m in ng	0.3
Characteristic adhesion force F_{H0} in nN	1.7
E-Modul E in kN/mm²	100
Micro-yield strength p_f in MPa	300
Stiffness $k_{N,el-pl}$ in N/m	2202
Critical time step t_{krit} in ns	0.2
Hamaker-Constant $C_{H,SLS}$ in 10^{-20} J	1.6
Contact friction coefficient μ_i	0.8

Surface functionalization and modification of glass particles

Hydrophilic



Hydrophobic



AFM, Nanoindentation, Compression & Shear tests

The modification process is shown on Ms. Kutelova's poster!

Results and Discussion

AFM	Nanoindentation	Compression test
Advantages		
+ Direct adhesion force measurement	+ High force and displacement resolution	+ High force and displacement resolution
Disadvantages		
- Insufficient resolution of the displacement	- No direct adhesion force measurement (only model based)	- No direct adhesion force measurement (only model based) - Only particle sizes > 200 µm

Material Data	AFM	Nano-indentation	Compression test
Particle size d_{50} in µm	17.3	17.3	520
Characteristic adhesion force F_{H0} in µN	0.9	219.5	$42.9 \cdot 10^6$
E-Modul E in kN/mm²	-	111.5	59.5
Elastic contact stiffness $k_{N,el,Sec}$ in N/mm	-	28.8	1375.9
Contact consolidation coefficient κ	-	0.01	-

Conclusions

✓ Influence of surface modification on the adhesion force

Unmodified particle

largest → Hydrophilic contact
large → Unmodified contact
low → Hydrophobic contact

DFG-Graduate School 1554 "Micro-Macro-Interactions in Structured Media and Particle Systems"