UNIVERSITY OF OXFORD

Imperial College London

Progress Since Washington Meeting

Challenge 1 and the PAMFJP project

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Context

- Previous Joints Workshops
  - New Orleans, 2001
  - West Palm Beach, 2002
  - Washington (Arlington, Virginia), 2006
- Report from Arlington meeting contained 3 ‘challenges’
  1. Experimental Measurement of Joint Properties
  2. Interface Physics
  3. Multi-scale modelling
- Formal progress on these challenges at a national/international level has been limited
  - But individual projects are taking place

Challenge 1 – Experimental Measurement of Joint Properties

- Standardisation of experimental techniques
  - Round-robin exercise to measure frictional hysteresis loops for a well-characterised material pair
- ‘Top-down’ Modelling
  - Draw on results of above to produce a ‘top-down’ model of the contact, based on an interface constitutive law
  - Use this to predict hysteresis loop in a different configuration (e.g. different roughness/different material pair/different geometry)

The PAMFJP project

- Predictive Approach to Modelling Frictional Joint Performance
- UK project, Funded by EPSRC
  - Collaborators: Imperial College London and University of Oxford
  - 4 years: October 2007 – Oct 2011
  - Research Assistant and Research Student at each institution.
  - Total Funding £0.75 million
- Industrial collaborators – Rolls-Royce plc and AWE

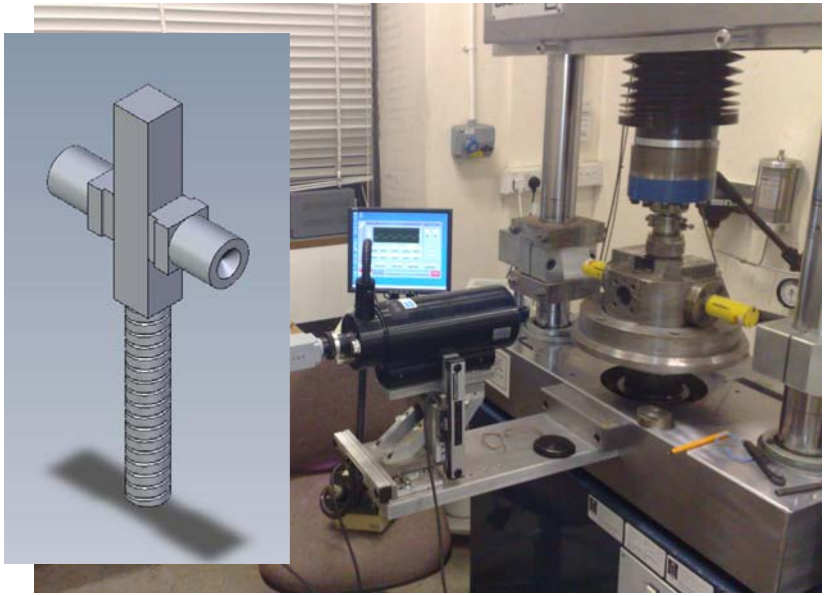
Staff

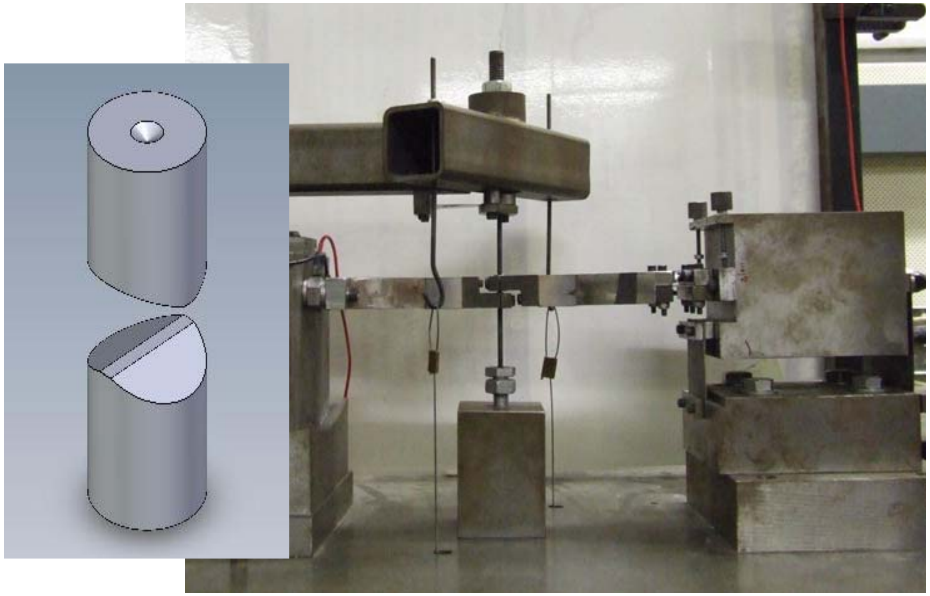
- Academic Staff
  - Prof David Ewins, Dr Evgeny Petrov, Vibrations – Imperial College
  - Dr Andy Olver, Dr Daniele Dini, Tribology – Imperial College
  - Prof David Nowell, Prof David Hills, - Solid Mechanics, Oxford
- Research staff and students
  - Simon Medina, Daniel Propentner, Christoph Scwingshackl, - Imperial
  - Mehmet Kartal, Daniel Mulvihill, - Oxford

Main work tasks

- Carry out independent hysteresis loop measurements on IC and Oxford equipment
  – Correlate results for friction coefficient and contact stiffness
- Development of physical understanding
  – Including measurements using SLIM apparatus
- Numerical modelling
  – Asperity level
  – Multi-asperity rough contact
- Validation
  – Prediction of response in different configuration

Oxford and Imperial rigs





- 80 mm^2 flat and rounded contact
- 1Hz Frequency
- 0.6mm sliding distance
- Displacement measurement by remote LVDT or digital image correlation

- 1 mm^2 flat on flat contact
- ~100Hz Frequency
- 30μm sliding distance
- Displacement measurement integration of LDV measurements

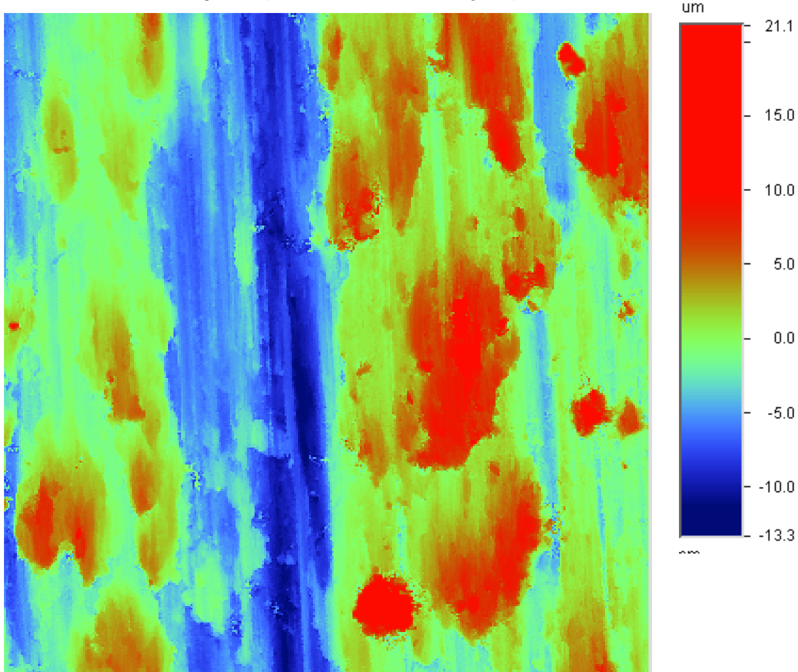
Materials

- Three material pairs chosen:
  - Ti6/4 ‘smooth’ ground
  - Ti6/4 ‘rough’ ground
  - Udimet 720 ‘smooth ground
- Specimens manufactured at Oxford to give ‘same’ surface finish for both specimen geometries
- Roughness of untested specimens measured at Imperial (Wyco) and Oxford (Alicona)

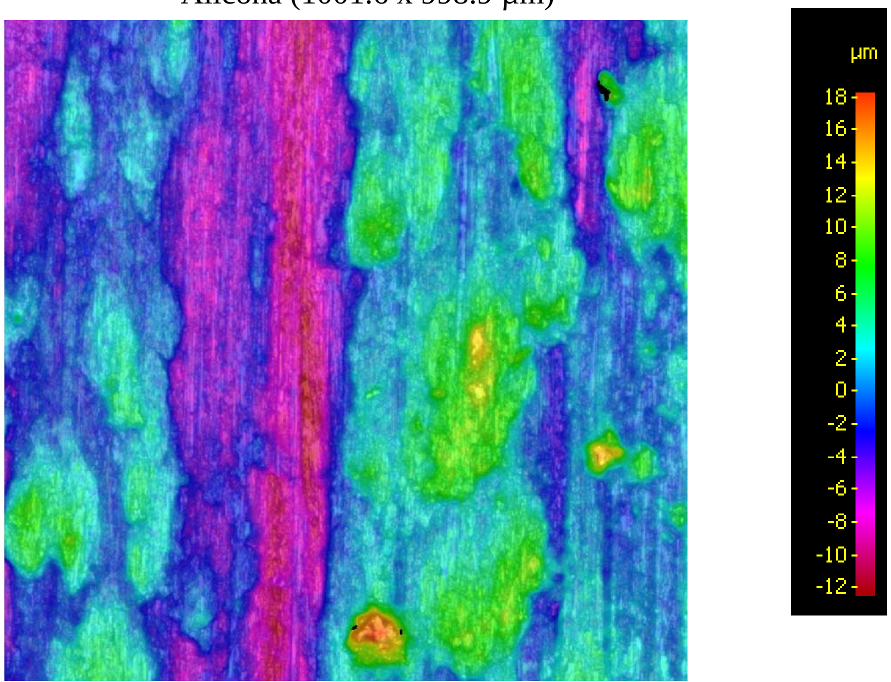
Roughness measurements
Alicona-Wyco Comparison

Titanium (TB58)	Wyco	Alicona
S_a	3.60 µm	3.56 µm
S_q	4.51 µm	4.47 µm
S_z	29.55 µm	30.76 µm
S_{ku}	2.91 µm	2.9 µm
S_{sk}	0.10 µm	0.073 µm

Wyco (1001.6 x 998.9 µm)



Alicona (1001.6 x 998.9 µm)



Comparison of Mean Roughness Values

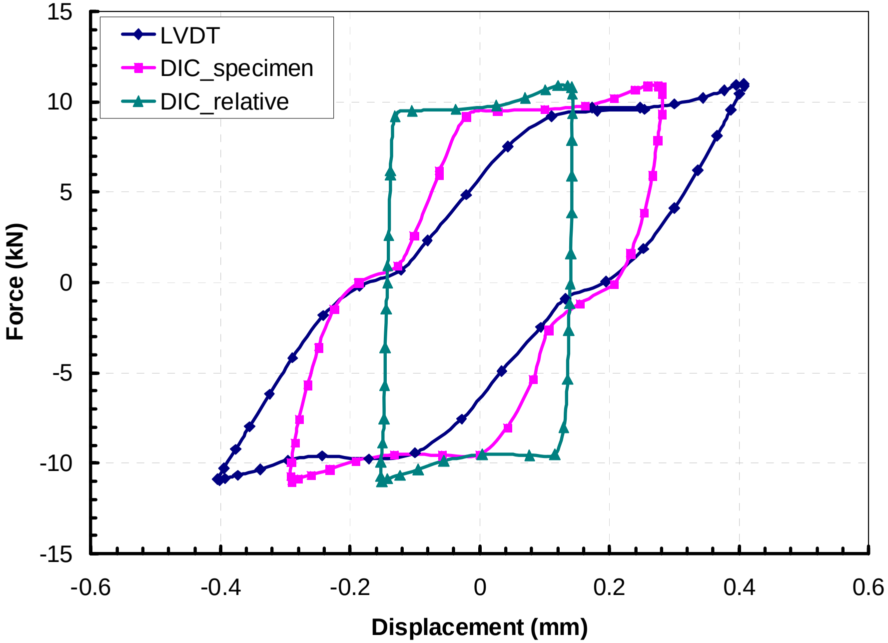
	S_a	S_q	S_P	S_v	S_Z	S_{10Z}	S_{sk}	S_{ku}	S_k	S_{pk}	S_{vk}
Titanium (Smooth) ALICONA	1.19	1.49	7.80	7.06	14.87	13.06	-0.012	3.04	3.76	1.34	1.43
Titanium (Smooth) WYCO	1.04	1.27			14.39						
Nickel ALICONA	1.54	1.88	8.92	7.88	16.79	15.46	0.038	3.07	4.68	1.72	1.76
Nickel WYCO	1.36	1.72			26.27						
Titanium (Rough) ALICONA	2.13	2.74	12.74	10.58	22.79	20.42	0.54	3.49	6.15	3.61	2.21
Titanium (Rough) WYCO	2.53	3.11			35.89						

•Wyco measurements were taken as average values of two perpendicular thin strips 574 x 6999 µm

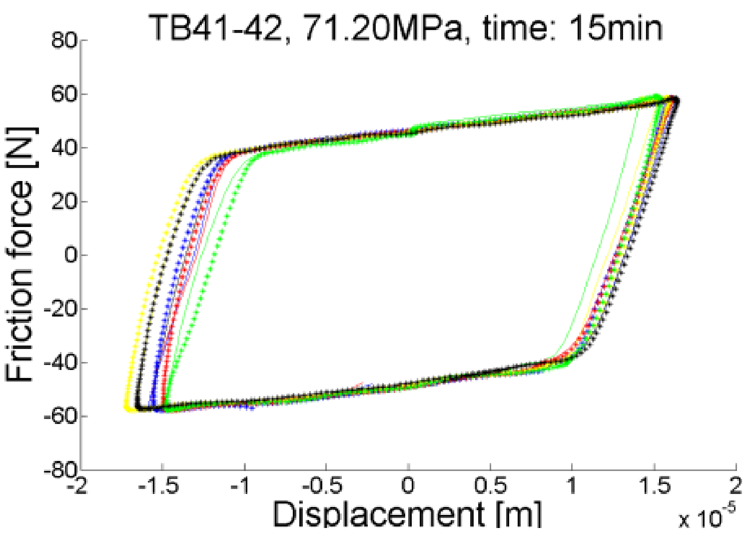
* All values in micrometers (µm)

Hysteresis loop measurements

Oxford



Imperial



- Both rigs show some change with time
  - Significant wear
- Similar features observed
  - E.g. rise in force during sliding phase
- Results obtained allow comparison of friction coefficient and stiffness values
  - Some issues still to be addressed (definition of μ, time, normalisation of stiffness

Comparison of results (provisional)

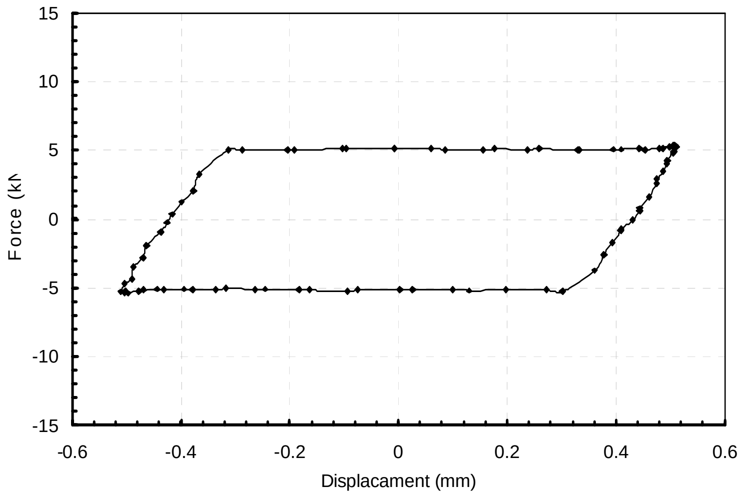
- Contact stiffness (N/m/mm of contact area)

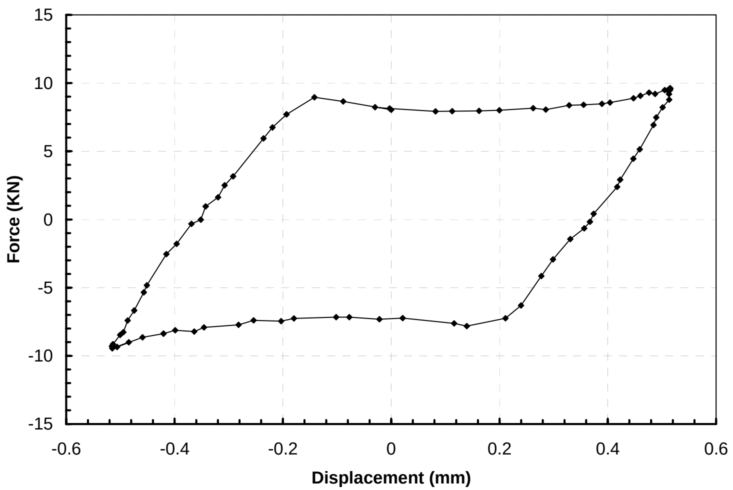
	Ti Smooth	Ti Rough	Nickel
Imperial	1.8×10^7	2.6×10^7	4.8×10^7
Oxford	Not yet measured with DIC	3.4×10^7	2.0×10^7

- Friction coefficient (after approx 3m sliding distance)

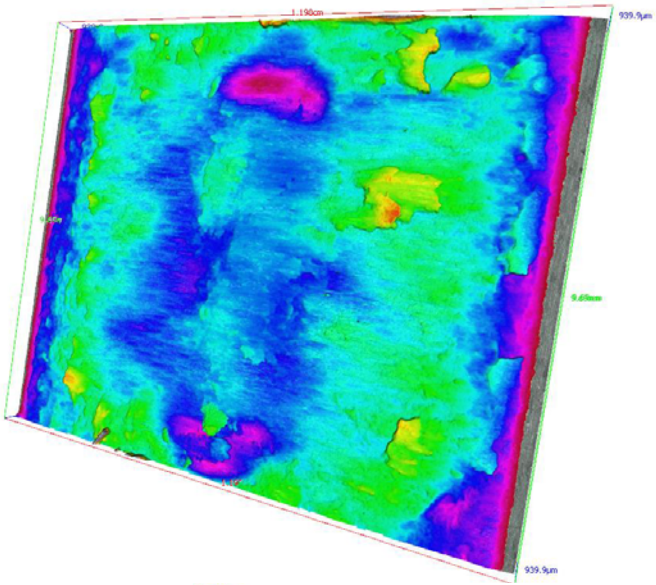
	Ti Smooth	Ti Rough	Nickel
Imperial	0.67	0.67	0.67
Oxford	0.61	0.71	0.69

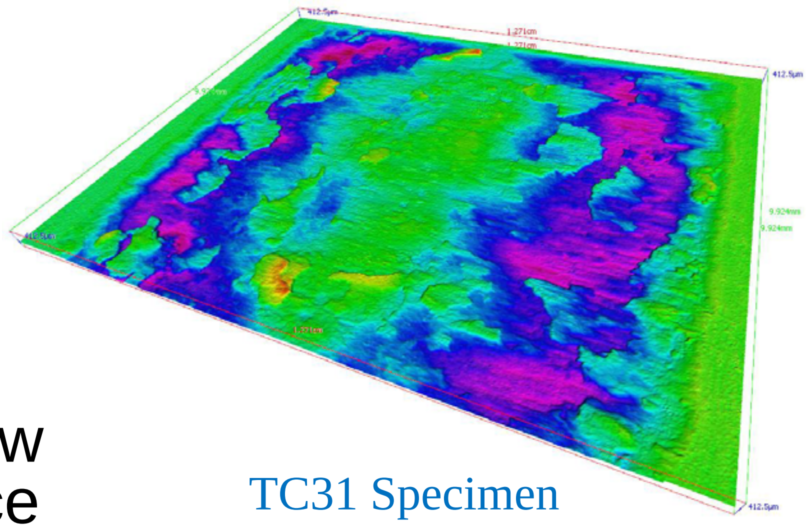
Variation of friction during test





TB55 Pad



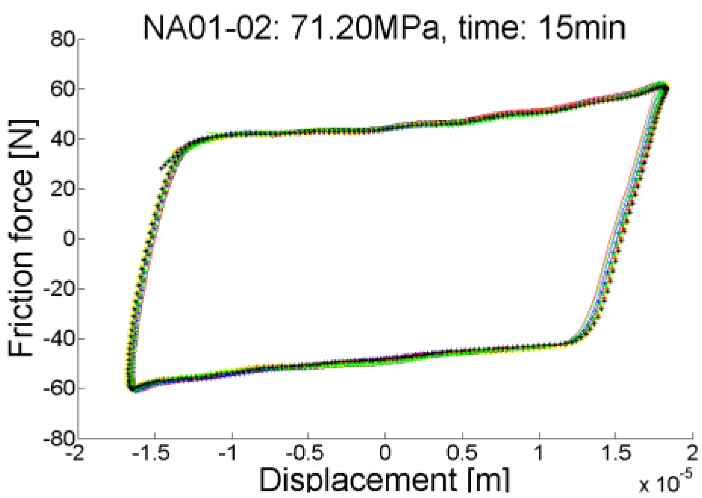


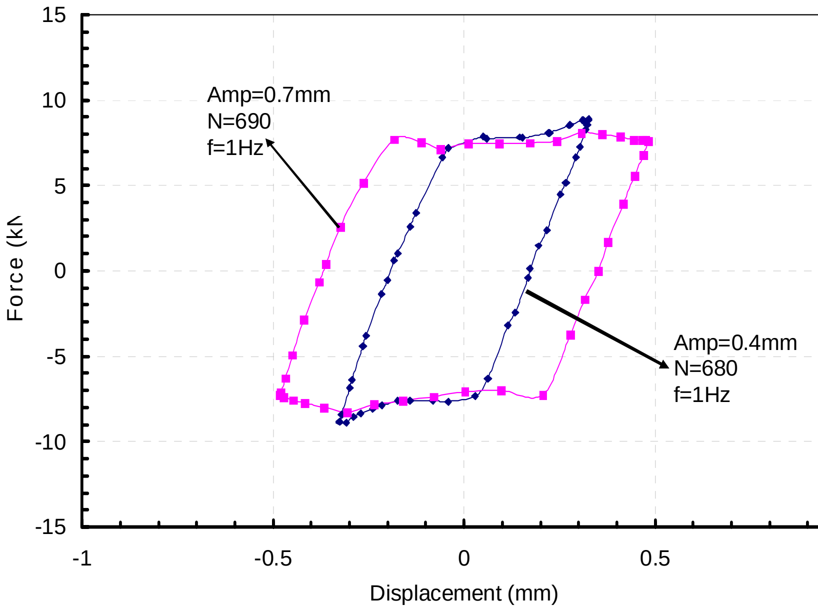
TC31 Specimen

- Roughness measurements show quite severe wear is taking place

Non-uniform friction during sliding

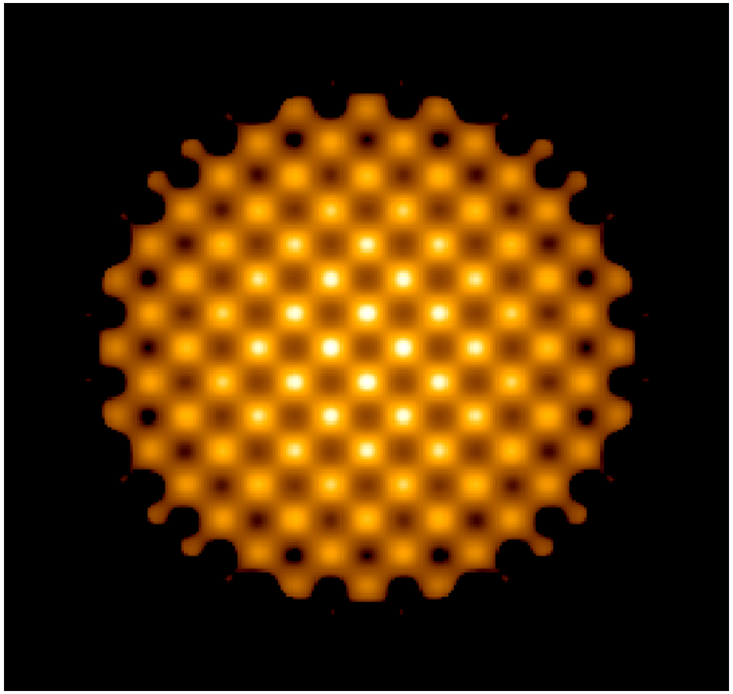
- Particularly in worn state, friction increases during sliding part of cycle
  – Seems to be associated with contact registration (macroscopic or microscopic?)
  – We have also discussed velocity dependent friction
  – Some variable amplitude tests carried out
  – Further work to be done



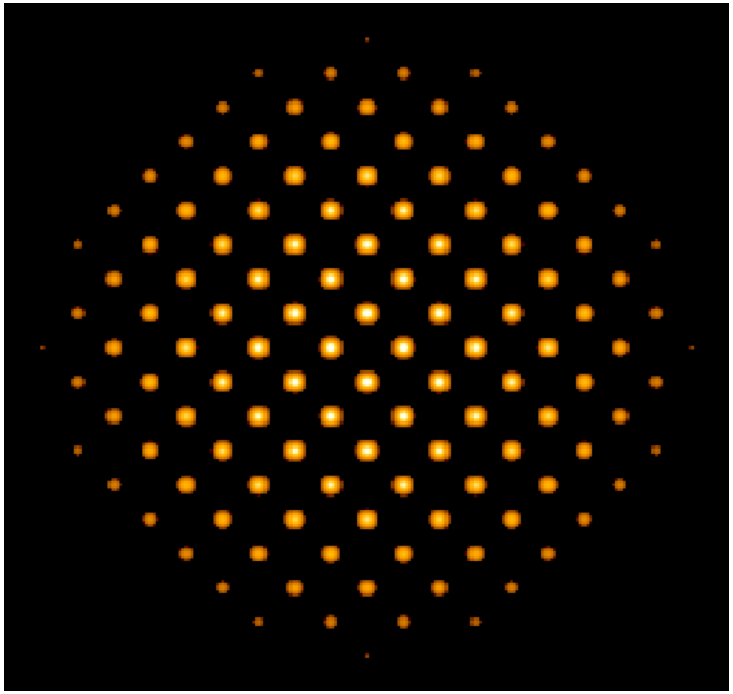


Modelling

- Simon Medina (IC) has developed model for elastic contact of rough surfaces using Venner/Lubrecht approach
- Coulomb friction can be included using Ciavarella method for partial slip

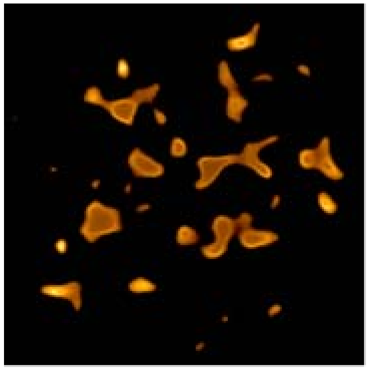


Amplitude 0.05 um

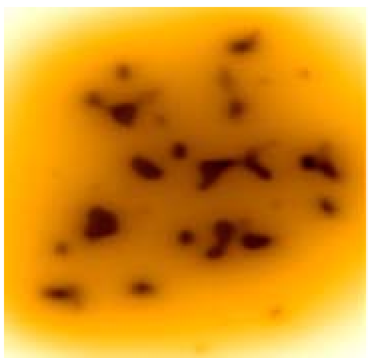


Amplitude 0.75 um

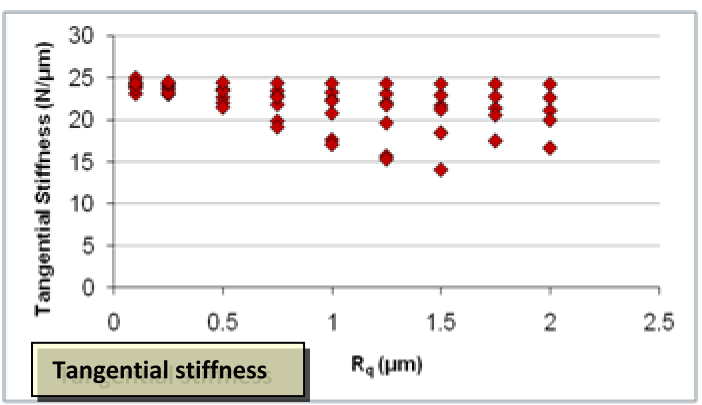
Partial slip modelling



Tractions



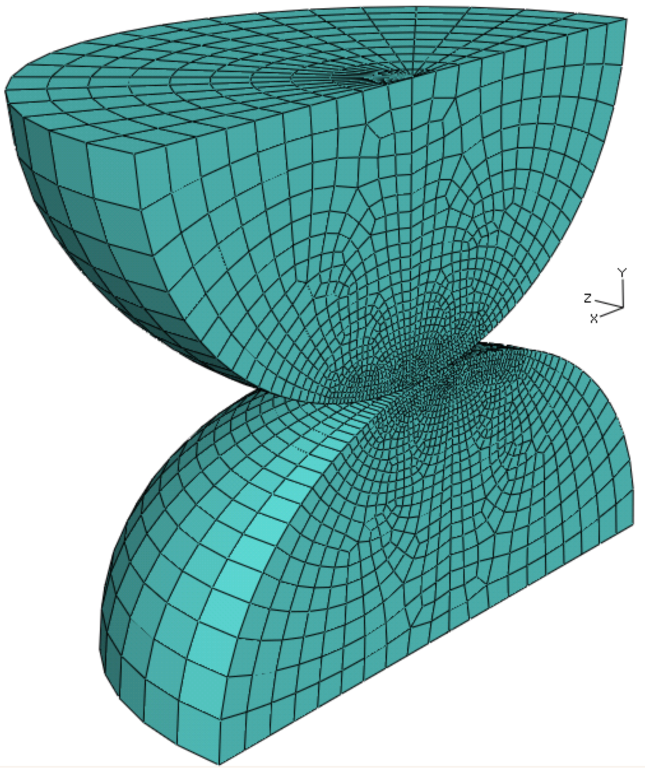
Slip

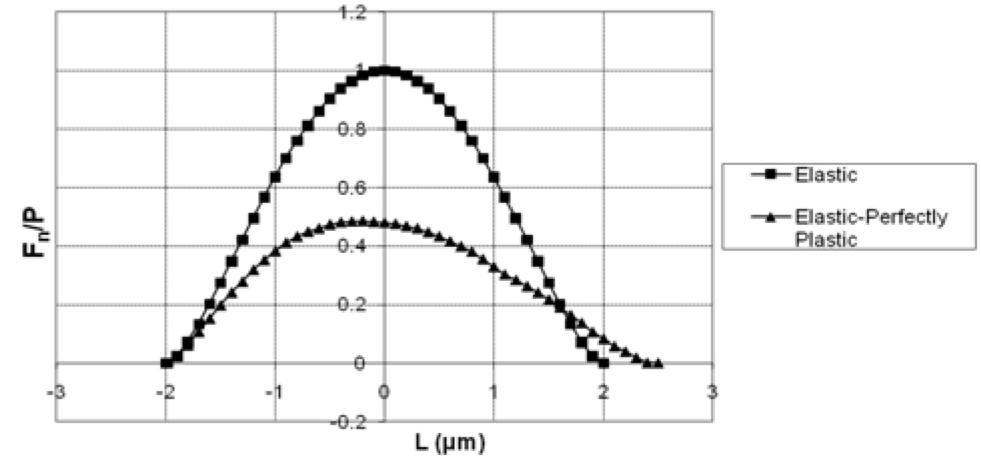


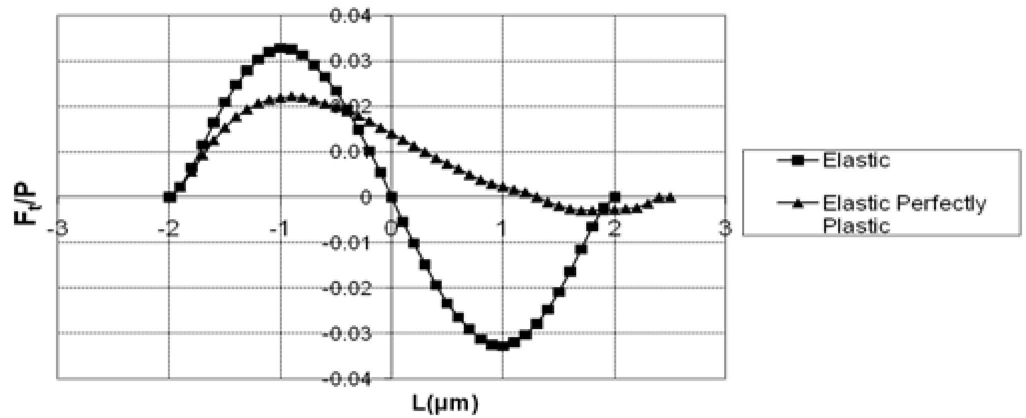
Currently possible	Further development req.d
Normal contact for any profile with/without adhesion and simplified plasticity [composite surface assumption]	Prediction of friction coefficient based on generalised measurable data
	Full plasticity solution
Tangential loading (incl. sequences) for non-adhesive contacts	Accounting for wear, and wear particles within contact
Prediction of friction loops for “suitable” contact geometries based on measured friction coefficient	<u>Prediction of friction loops for contacts such as Imperial and Oxford test rigs</u>
	Tangential loading with adhesion

Modelling at the asperity scale

- Daniel Mulvihill (Oxford) has undertaken FE modelling of interaction of a pair of elastic-plastic asperites







Conclusions

- Challenge 1 from Arlington Meeting has not yet been addressed internationally in a co-ordinated way
- However, it has been used nationally as the basis for collaborative projects
- An example of this is the Oxford/Imperial PAMFJP project
- Significant progress made in understanding and correlating experimental measurements on different rigs
- Work still ongoing in modelling at a single asperity or multi-asperity level
- Wear is more significant than was originally thought when defining the project