Friction and wear reduction using ultrasonic lubrication

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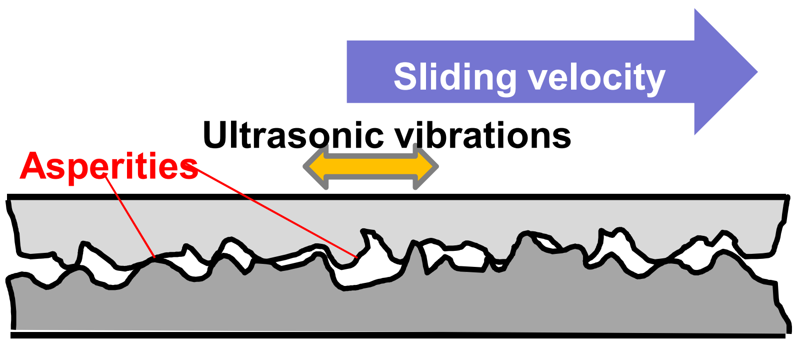
Outline

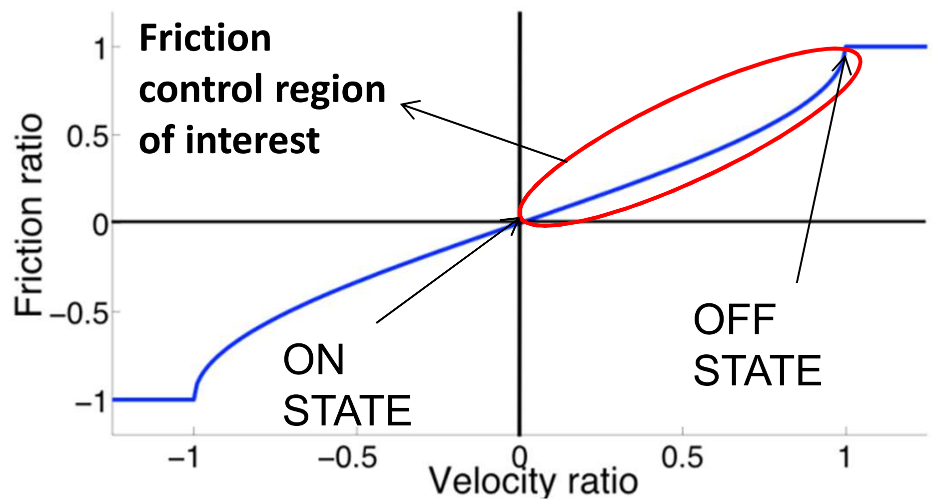
- Background on ultrasonic lubrication
- Experiments
  - Stainless steel pin on aluminum disc
  - Ceramic & M50 steel pins on M50 steel disc
  - Steel on skin replica
  - Power mapping
  - Comparison between different lubrication methods
- Cube model
- Concluding remarks

Ultrasonic Lubrication Principle

Ultrasonic lubrication: the coefficient of dynamic friction between two surfaces decreases when ultrasonic vibrations are superimposed to the macroscopic sliding velocity

- This form of friction reduction is "solid state" and **requires no greases or oils**
- We use a **piezoelectric actuator** to create ultrasonic vibrations. Piezoelectric actuators are **extensively used** in consumer electronic products.
- Modulate the friction coefficient between "high friction" (**off state**) and "low friction" (**on state**) by driving the actuator at different voltages

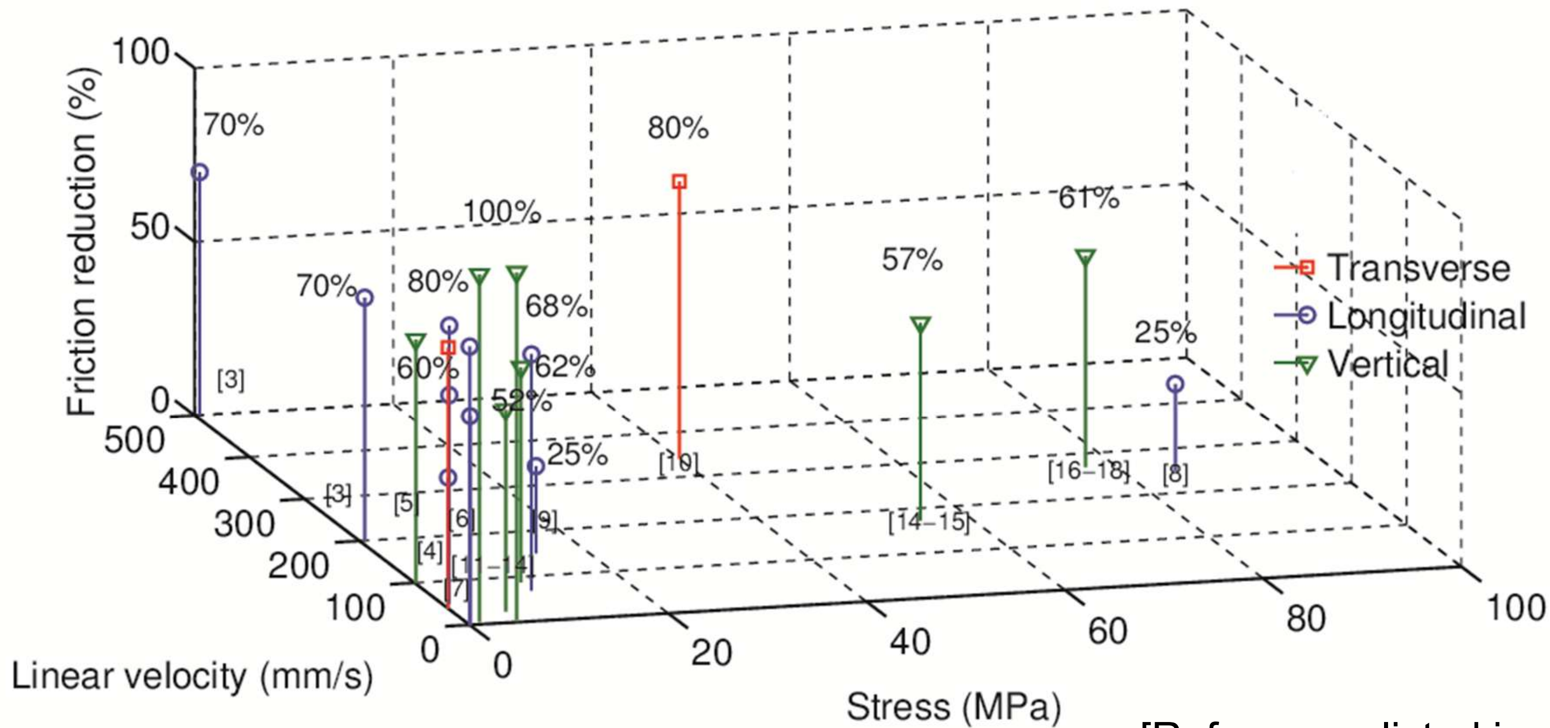




$$\text{Friction ratio} = \frac{\text{Friction with ultrasonics}}{\text{Friction without ultrasonics}}$$

$$\text{Velocity ratio} = \frac{\text{Sliding velocity}}{\text{Vibration velocity}}$$

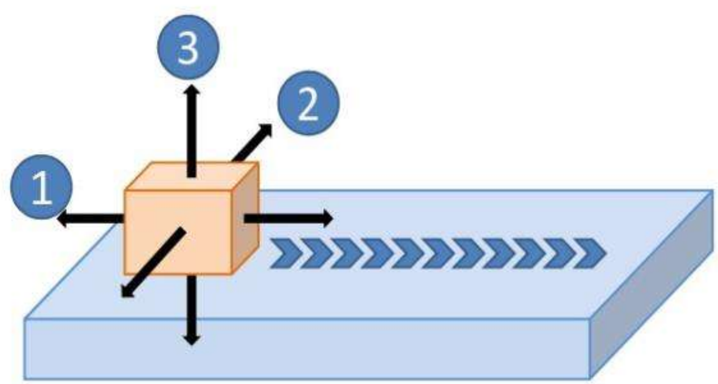
State of the Art



[References listed in appendix]

Other Factors

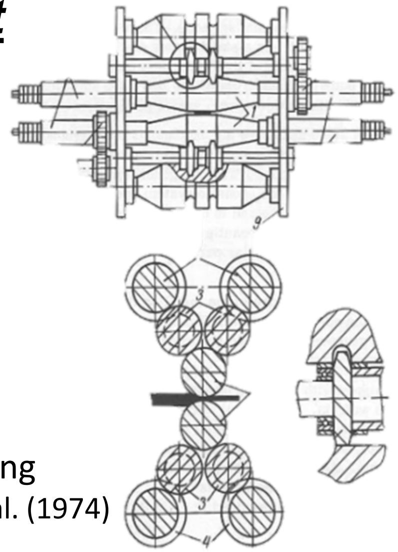
- Friction type: dry sliding, lubricated sliding, and rolling
- Materials: steel, stainless steel, aluminum, copper, brake pad, glass, titanium, brass, Teflon, and rubber among others.



Applications

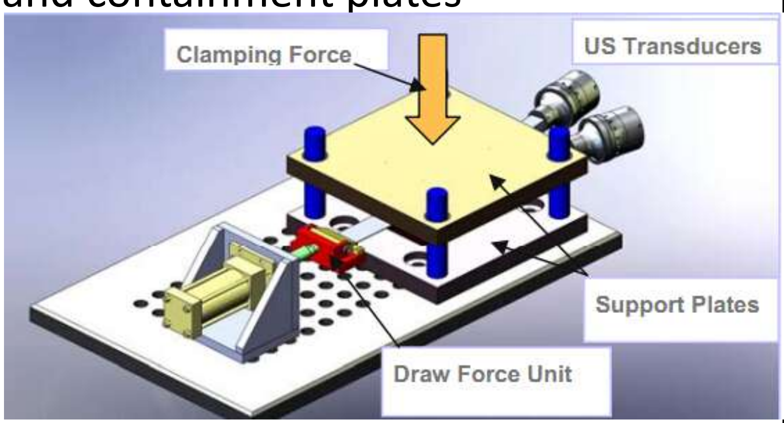
Past

Metal forming:
- Stamping
- Sheet rolling
- Wire drawing
- Compressing



Sheet rolling
Severdenko et al. (1974)

Thermal stir welding:
Reduce friction between workpiece and containment plates



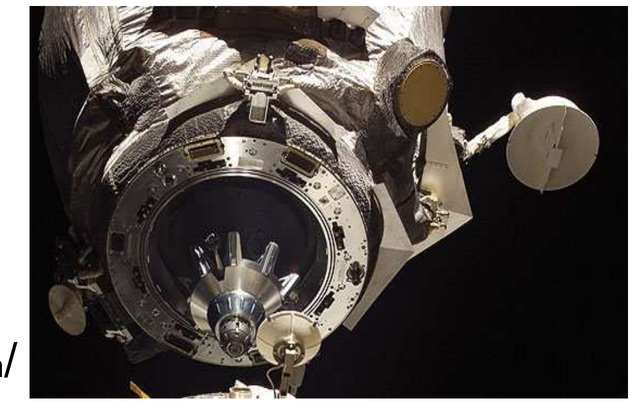
EWI test bed

Future

Consumer products:
Reduce friction to enhance user experience

http://www.thanksmailcarrier.com/

Space mechanisms:
Reduce friction and wear where traditional lubrication is not possible



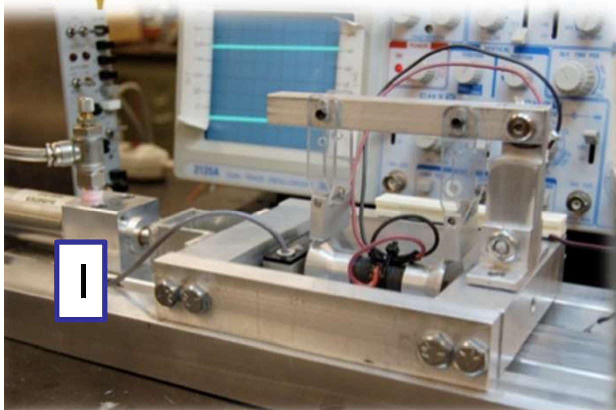
http://www.spacetelescopes.com/

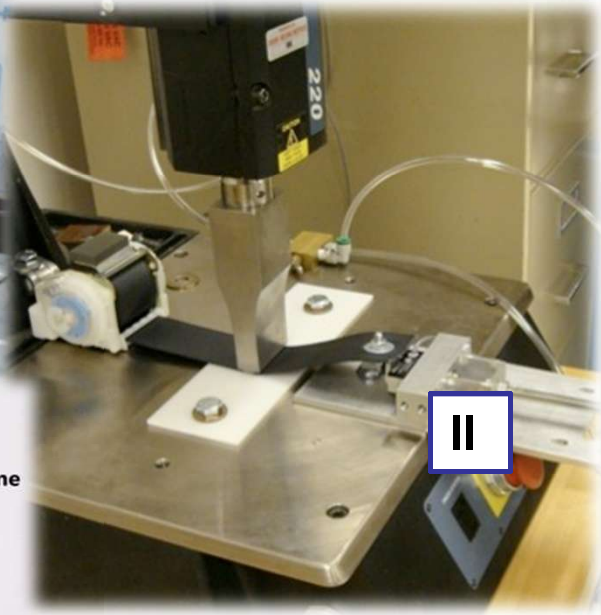
Vehicle applications:
- Ball joints
- Seat rails
- Steering mechanisms
- Powertrain components

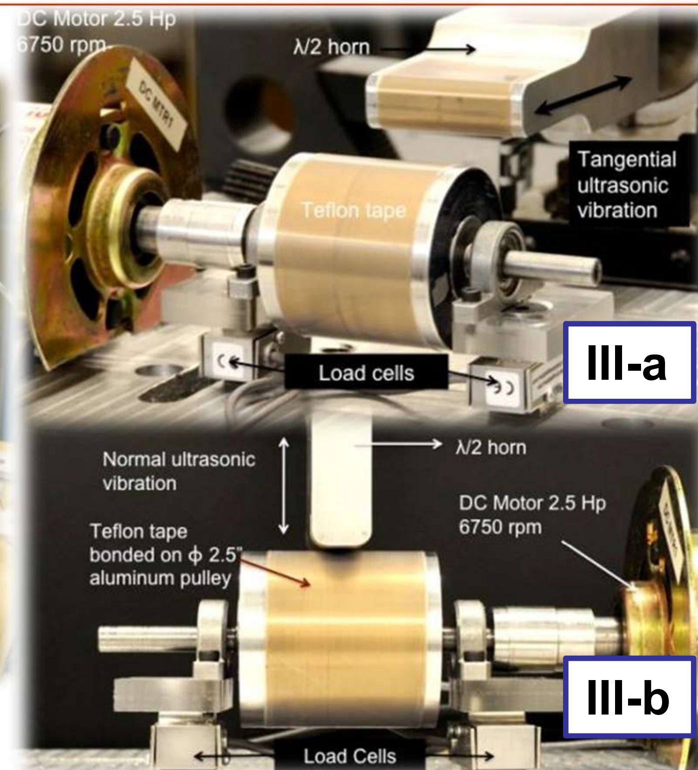
http://www.japshop.co.uk/

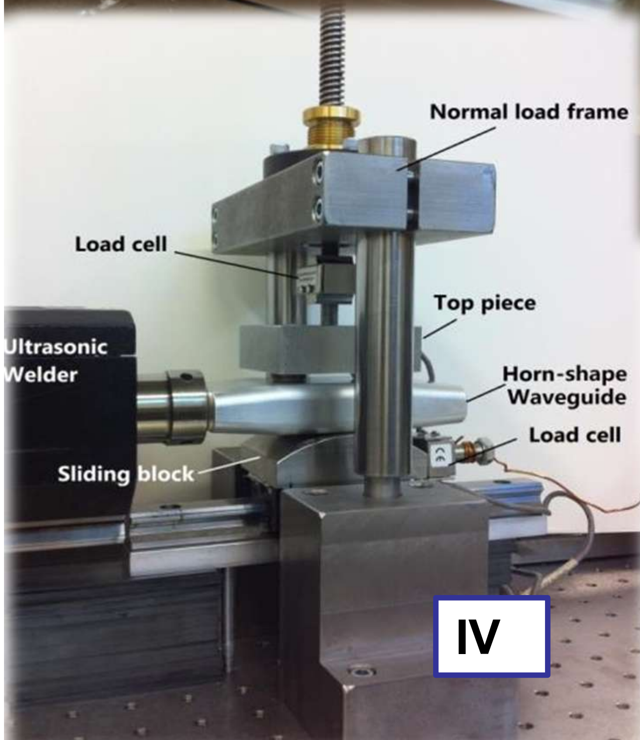
http://www.eurocarnews.com

Previous Experiments



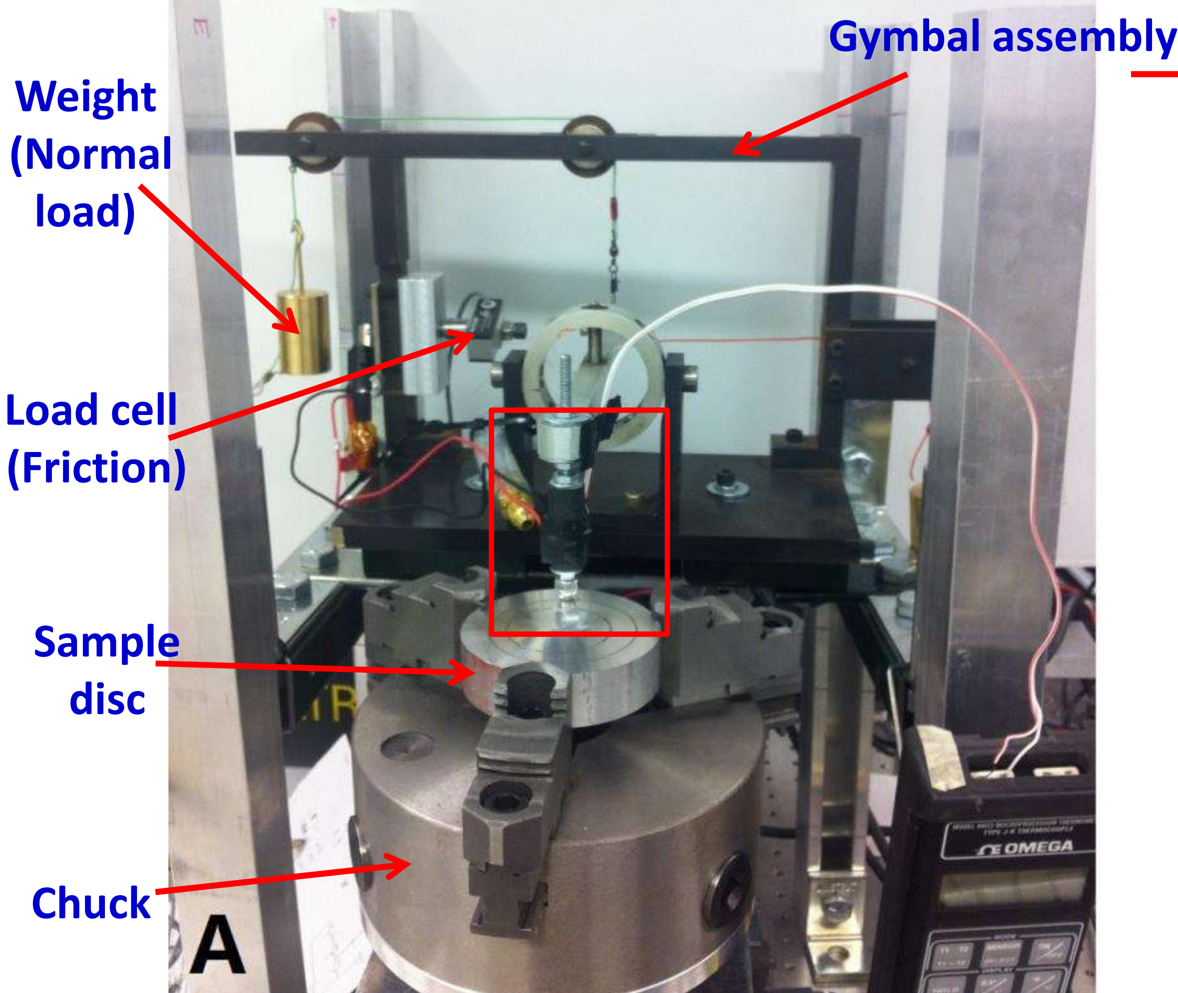




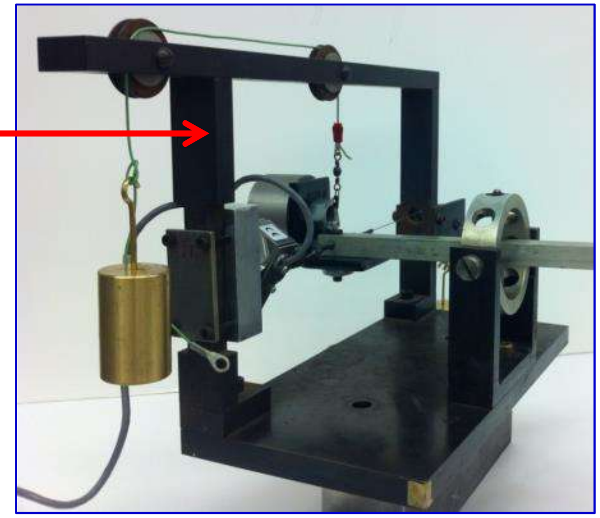


Setup	Velocity [mm/s]	Load [N]	Power [kW]	Max Friction Reduction %
I	68	10	0.012	68
II	25	670	2.2	58
III-a	5810	40	2.2	22
III-b	5810	90	2.2	82.35
IV	5	60-240	2.2	100

Modified Pin-on-disc Tribometer

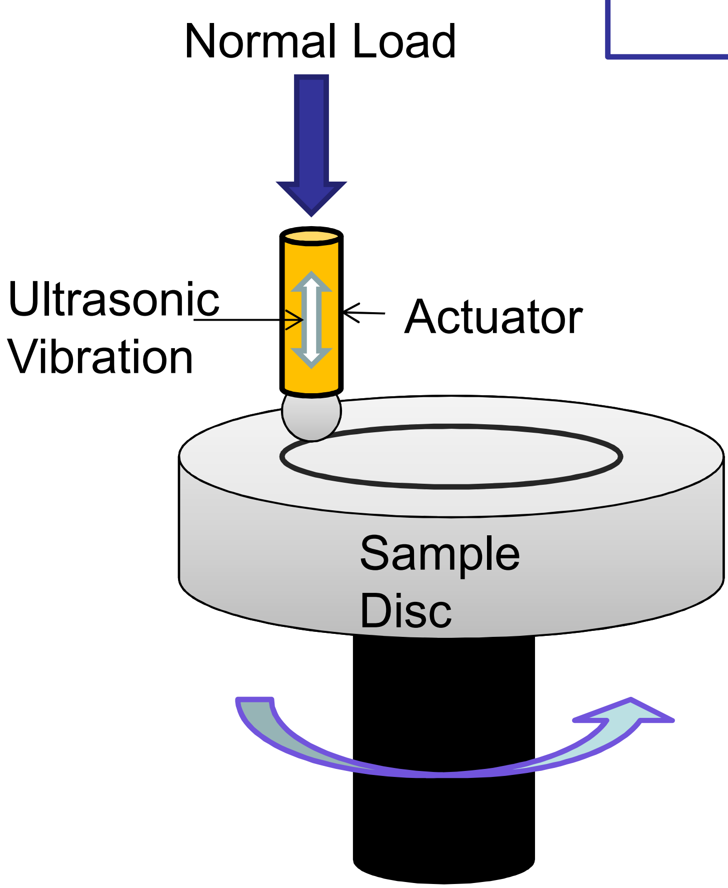


Front View



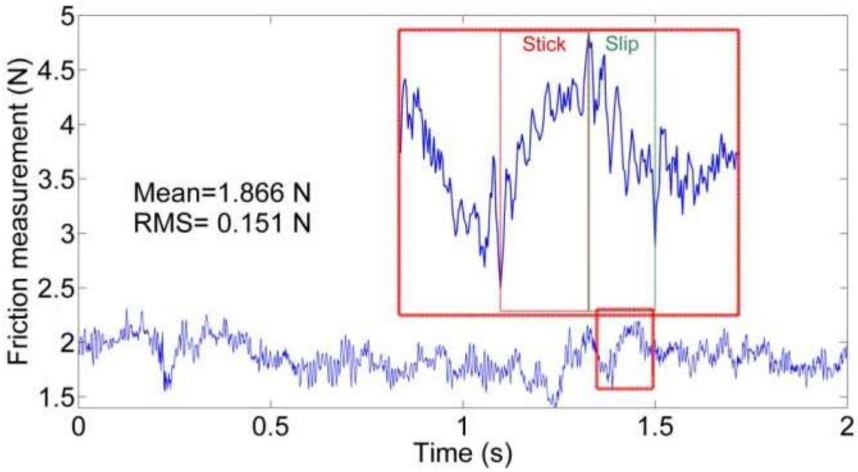
Schematics and Parameters

This study is conducted to investigate the relationship between wear reduction and **linear velocity**



Parameter	Value		
Group	1	2	3
Linear Velocity (mm/s)	**20.3**	**40.6**	**87**
Running time (h)	4	2	0.93
Distance travelled by pin (m)	292.5		
Normal load	3 N		
Revolutions	1600		
Disc run out (mm)	± 0.0286		
US frequency (kHz)	22		
US amplitude (μm)	2.5		
Pin material	Stainless steel 316		
Disc material	Aluminum 2024		
Nominal groove diameter (mm)	50		
Sampling frequency (Hz)	400		

Friction Reduction

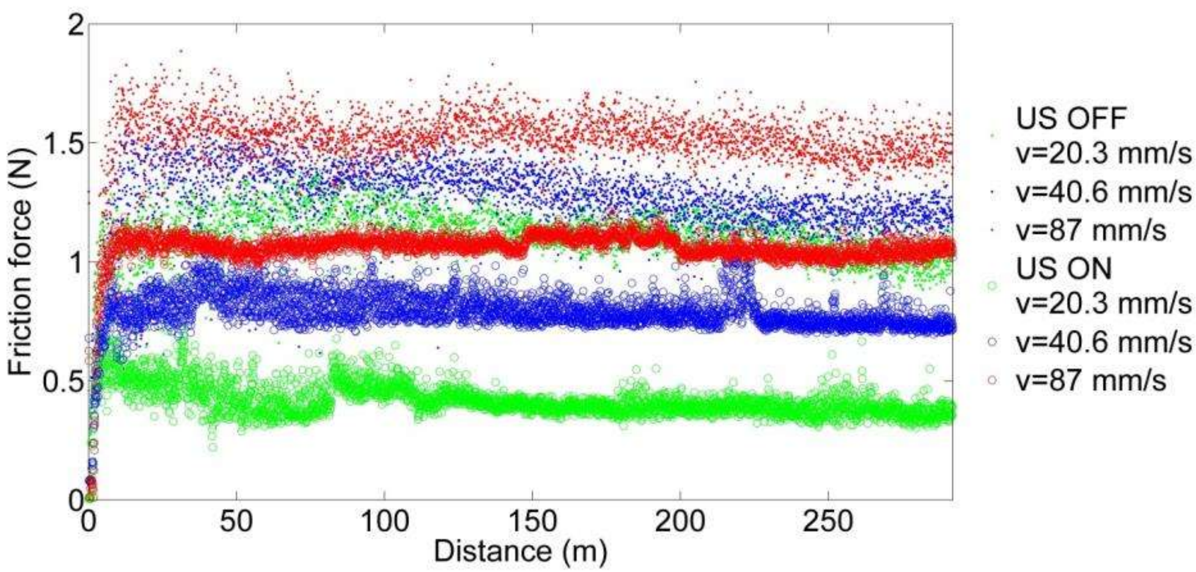


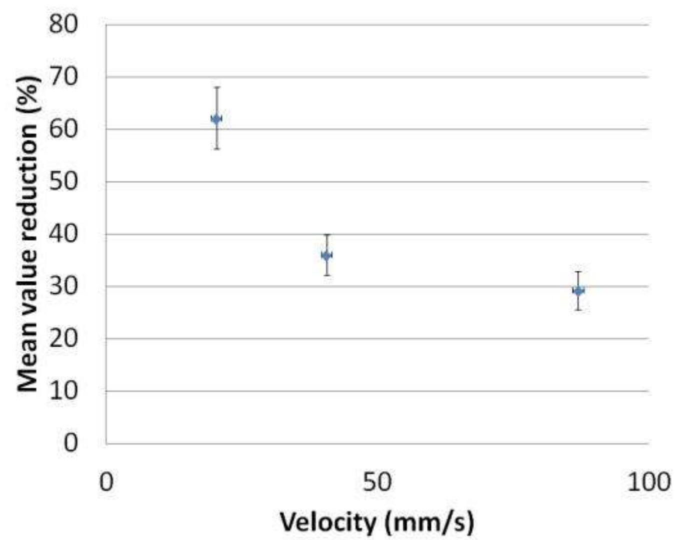
- Reduction percentage is defined as

$$P_f = \frac{f_0 - f_1}{f_0} \times 100$$

where f_0 is the intrinsic friction and f_1 is the new (reduced) friction.

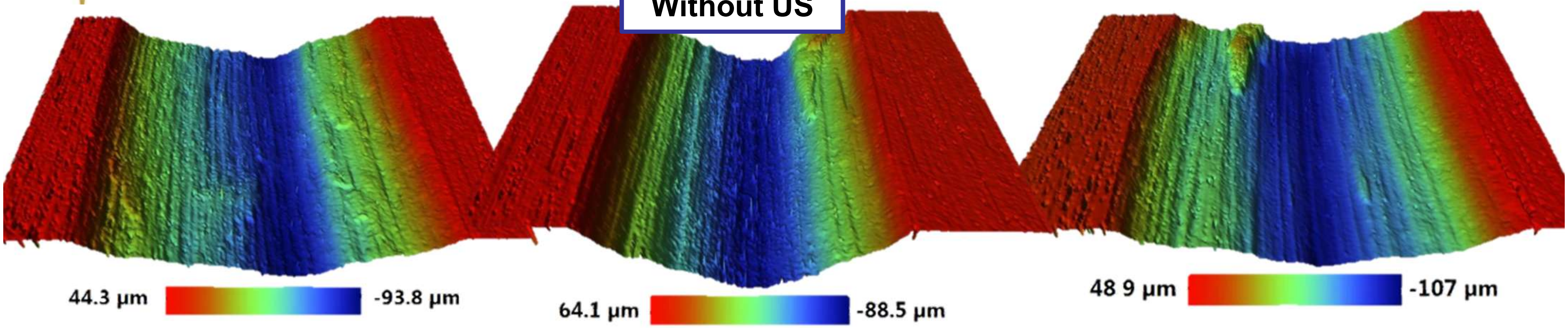
- All three groups show reduction of steady state friction force. Friction reduction decreases as velocity increases.





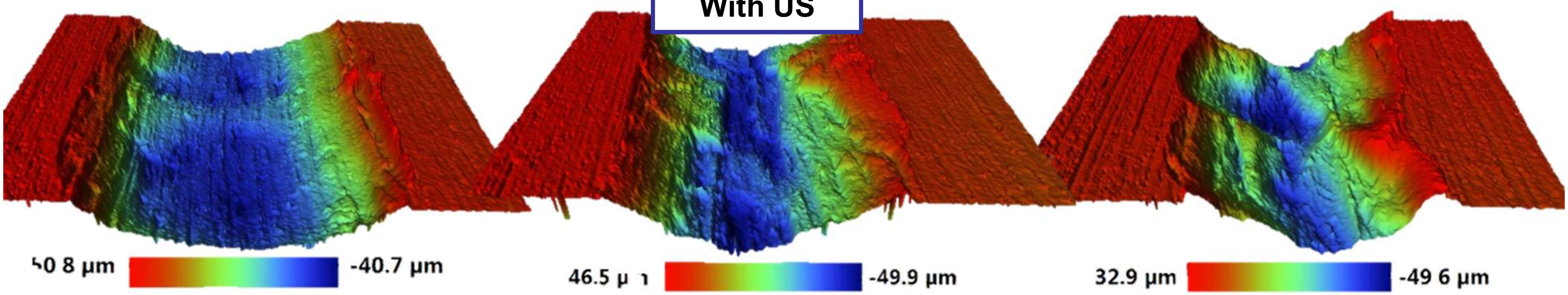
Wear Reduction

Without US



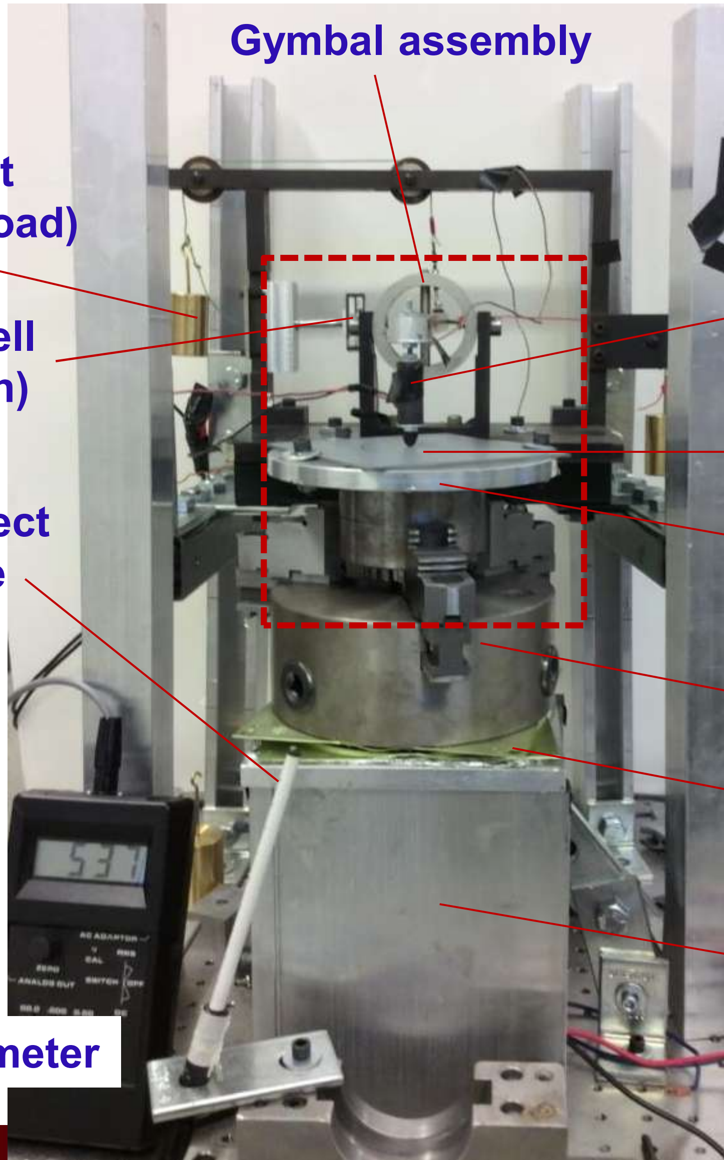
v= 20.3 mm/s **v= 40.6 mm/s** **v= 87 mm/s**

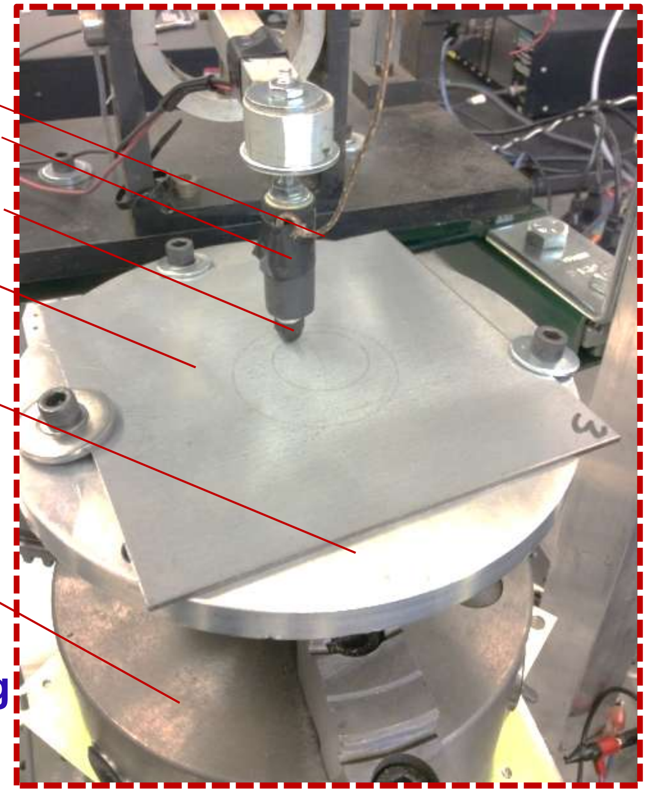
With US



Linear velocity (mm/s)	Wear rate without US (mm^3/m)	Wear rate with US (mm^3/m)	Wear Reduction (mm^3/m)	Number of Contacts	Wear Reduction (%)
20.3	2.237×10^{-2}	1.214×10^{-2}	1.023×10^{-2}	3.17×10^{8}	**45.76**
40.6	2.581×10^{-2}	1.338×10^{-2}	1.243×10^{-2}	1.58×10^{8}	**48.18**
87	2.430×10^{-2}	1.248×10^{-2}	1.182×10^{-2}	7.39×10^{7}	**48.63**

Modified Pin-on-disc Tribometer for Power Mapping

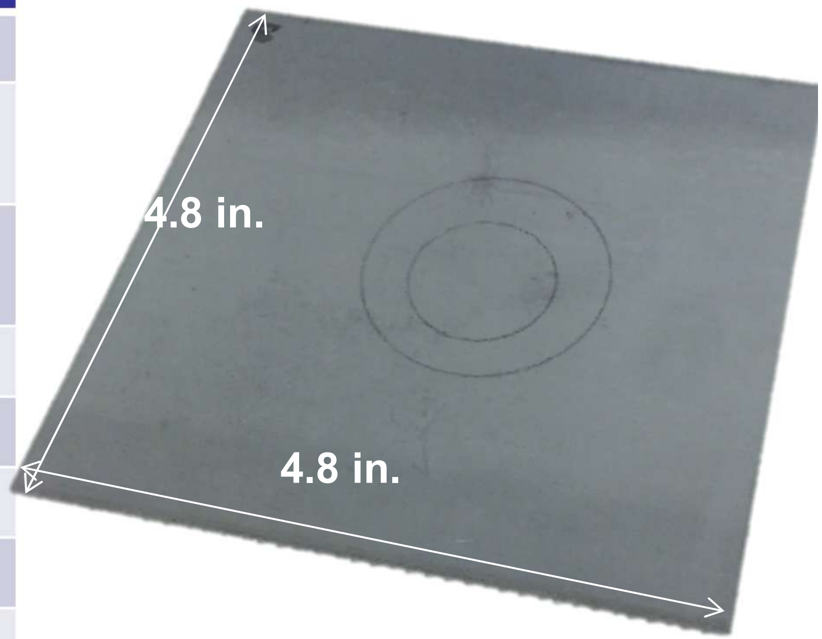




Parameters

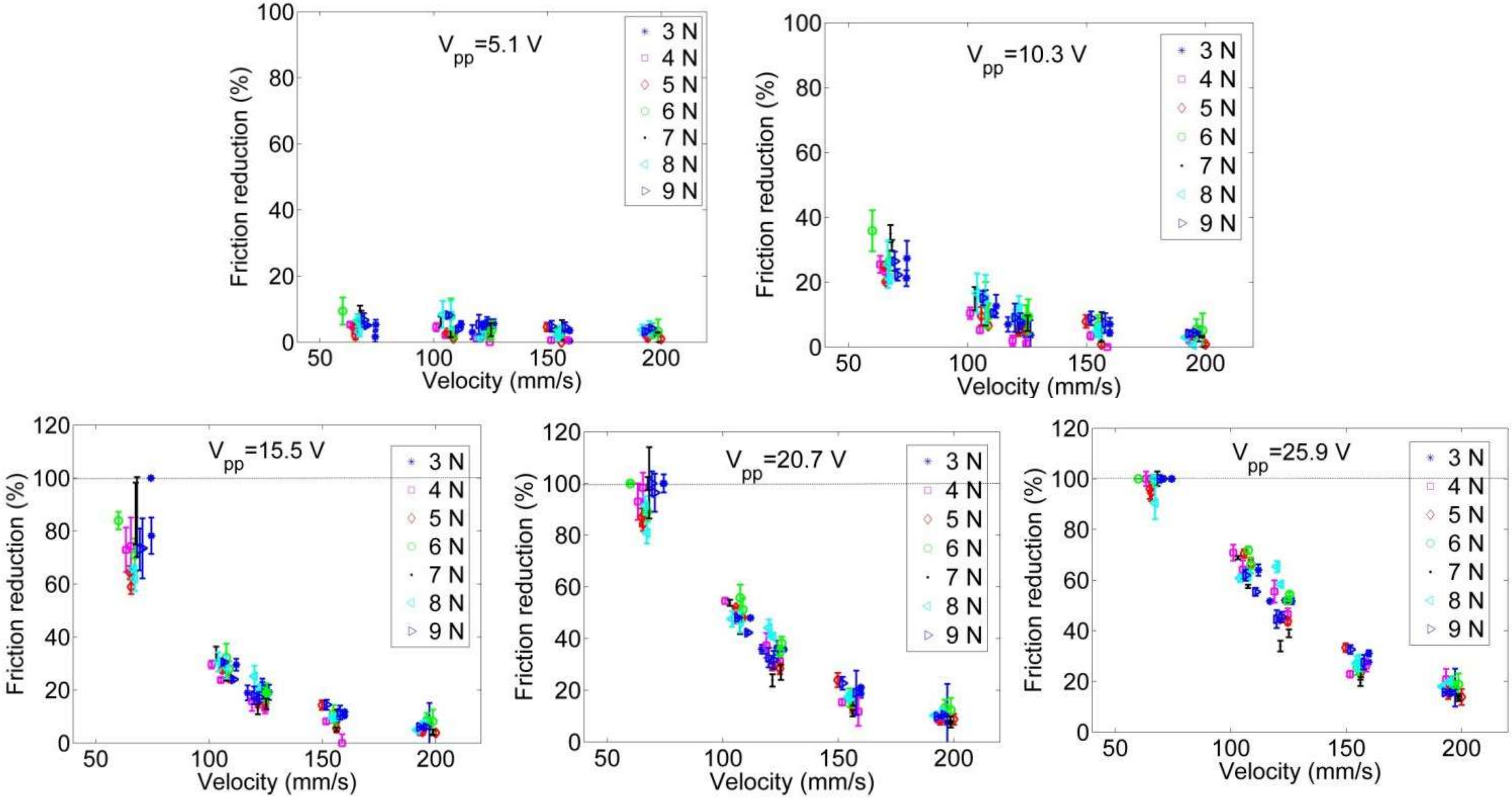
Parameter	Value
Normal load (N)	3, 4, 5, 6, 7, 8, 9
Nominal contact area (mm^2)	0.126
Nominal normal stress (MPa)	23, 32, 40, 48, 55, 63, 70
Rotational diameter (mm)	28, 48.3
Linear velocity (mm/s)	50-200
Peak-to-peak voltage (V)	0, 5.1, 10.3, 15.5, 20.7, 25.9
Actuator capacitance (nF)	360
Power consumed by the actuator (W)	0, 0.21, 0.84, 1.9, 3.39, 5.31
Nominal US amplitude (µm)	0, 0.46, 0.92, 1.38, 1.85, 2.31
US frequency (kHz)	22
Material	Uncoated steel for pin and disc

Sample plate



- 7 plates in total
- One stress assigned to one plate

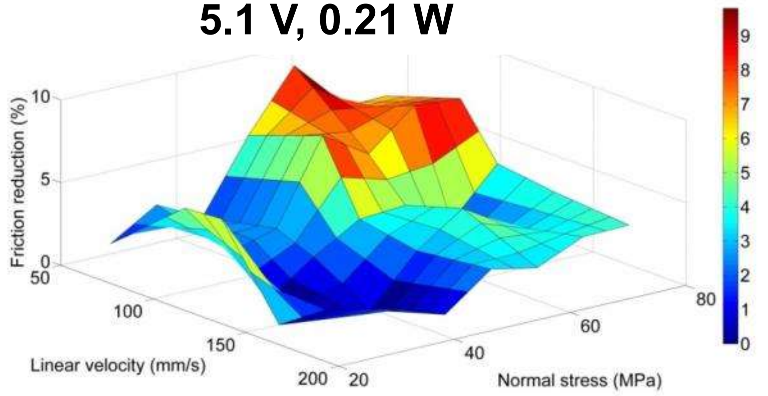
Friction Reduction vs. Linear Velocity



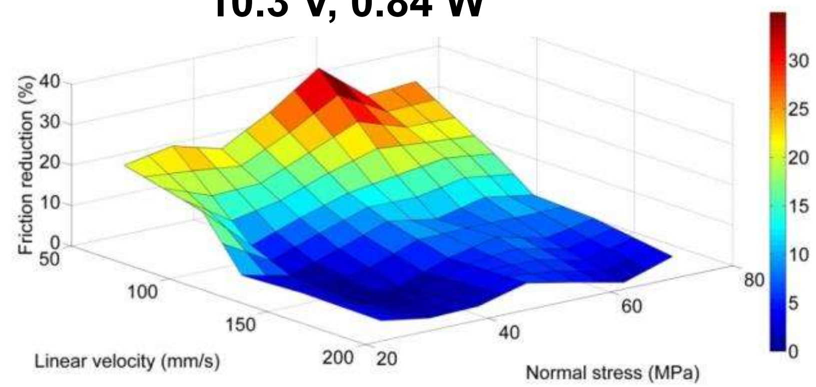
Note: Noise and measurement errors cause some data markers to show greater than 100% friction reduction.

Relationship between Friction Reduction, Linear Velocity and Normal Stress

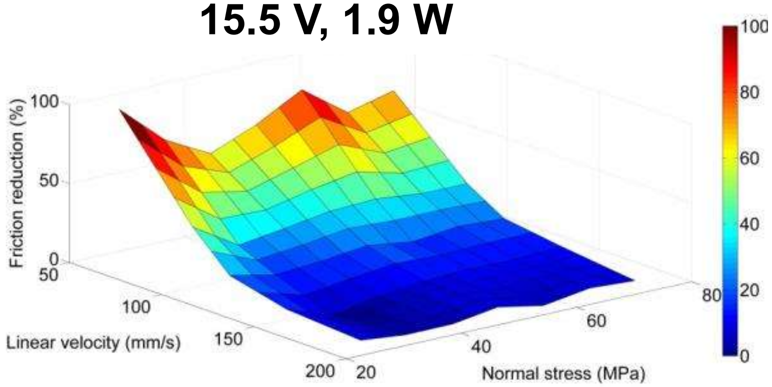
5.1 V, 0.21 W



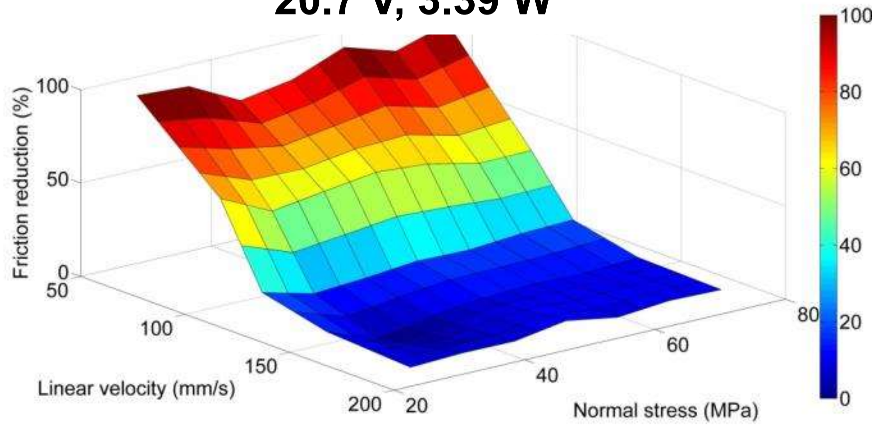
10.3 V, 0.84 W



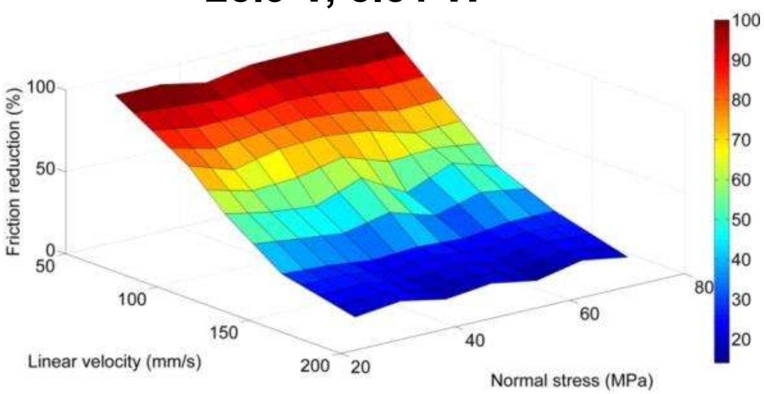
15.5 V, 1.9 W



20.7 V, 3.39 W



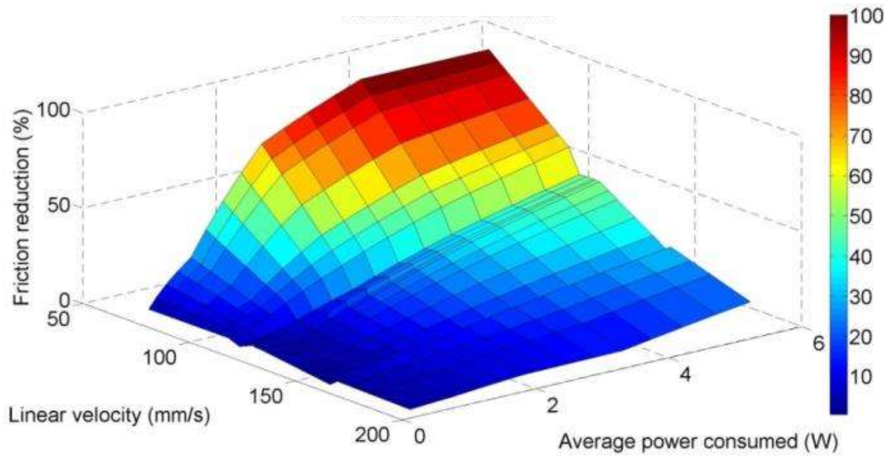
25.9 V, 5.31 W



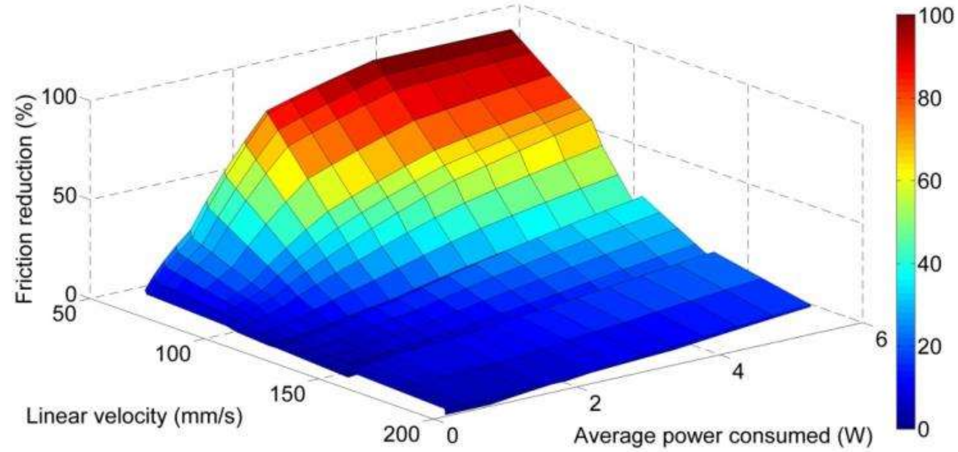
- Friction reduction peaks at 48 and 55 MPa normal stress, especially at low velocities.
- A dynamic model, incorporated with a “cube” model [15], is employed to explain the cause of the peaks.

Relationship between Friction Reduction, Linear Velocity, and Power Consumption

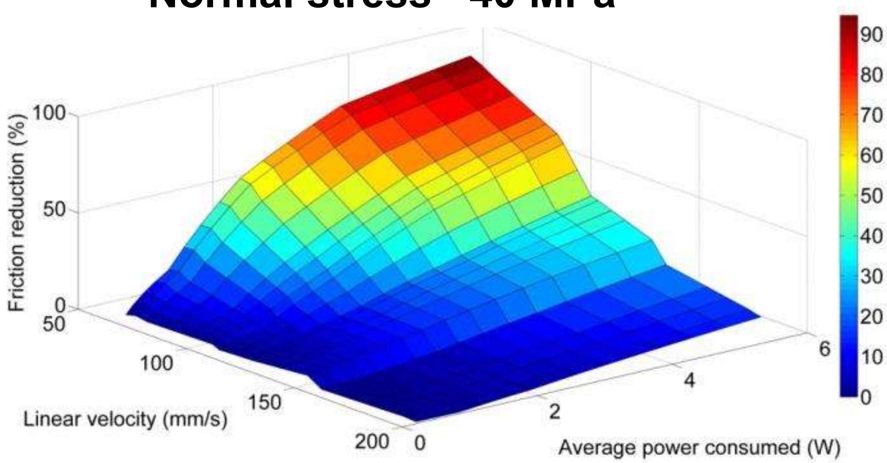
Normal stress= 23 MPa



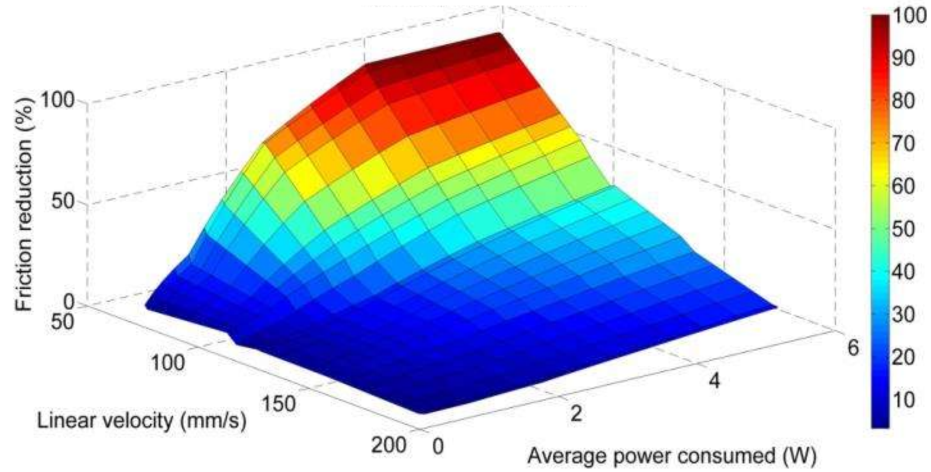
Normal stress= 55 MPa



Normal stress= 40 MPa



Normal stress= 70 MPa



Energy, Power, and Efficiency Metrics

Reduced friction

Relative velocity

Intrinsic friction

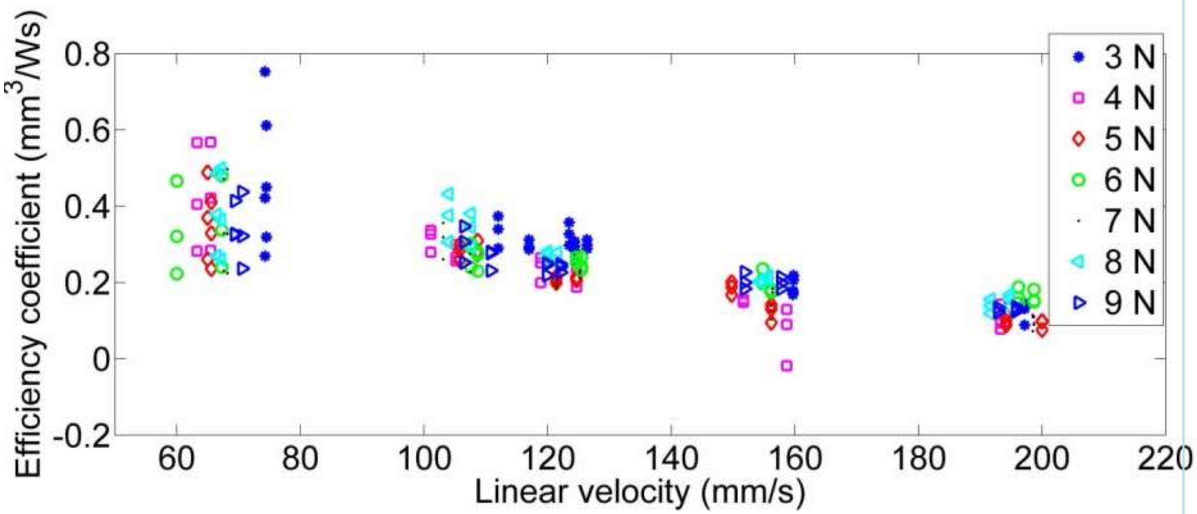
Nominal contact area

Efficiency coefficient

$$\eta = \frac{(F_{t0} - F_{t1}) v_{rel} A_n}{F_N P_a}$$

Normal load

Power consumed by the actuator



$$\eta = a v_{rel} + b$$

The efficiency coefficient can be used to:

(a) Estimate new (reduced) friction force for a given electrical power supply

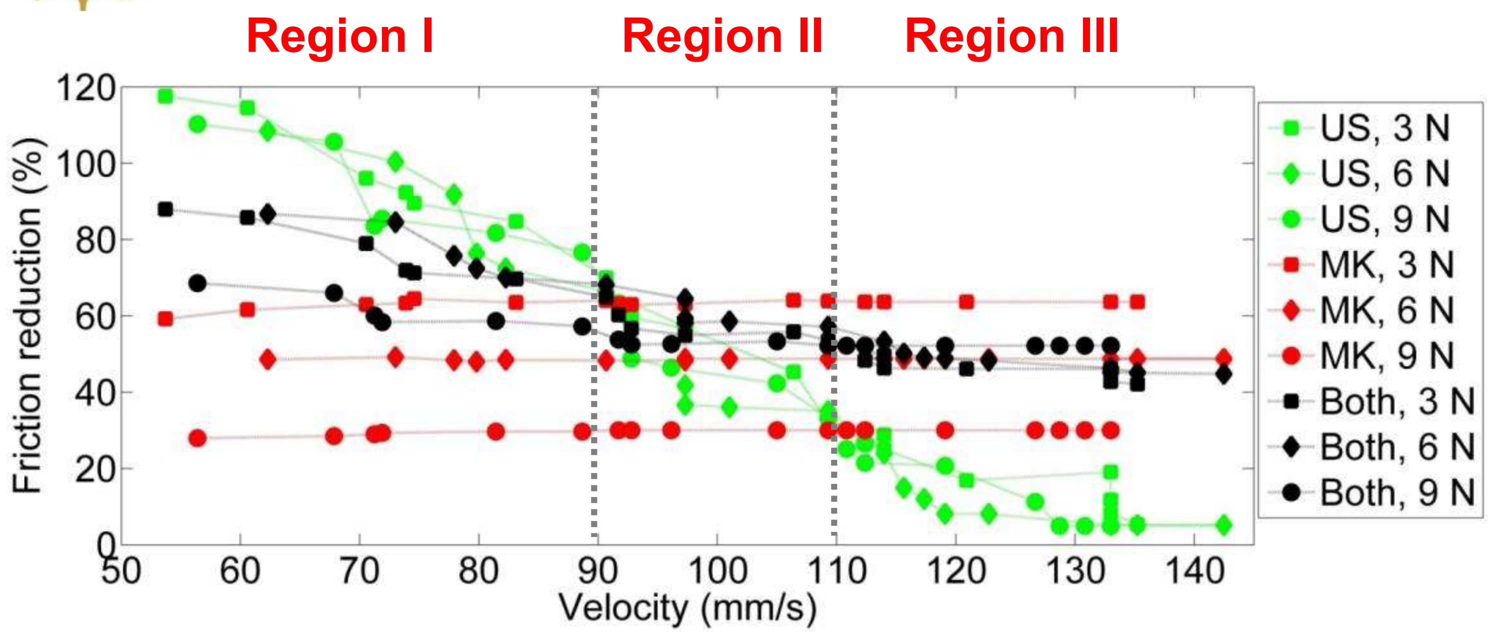
$$F_{t1} = F_{t0} - \frac{F_N (a v_{rel} + b) P_a}{v_{rel} A_n}$$

(b) Estimate power requirement for a given amount of friction reduction

$$P_a = \frac{(F_{t0} - F_{t1}) v_{rel} A_n}{F_N (a v_{rel} + b)}$$

(c) Enable ultrasonic friction control

Comparison between Lubrication Methods



US: Ultrasonic lubrication

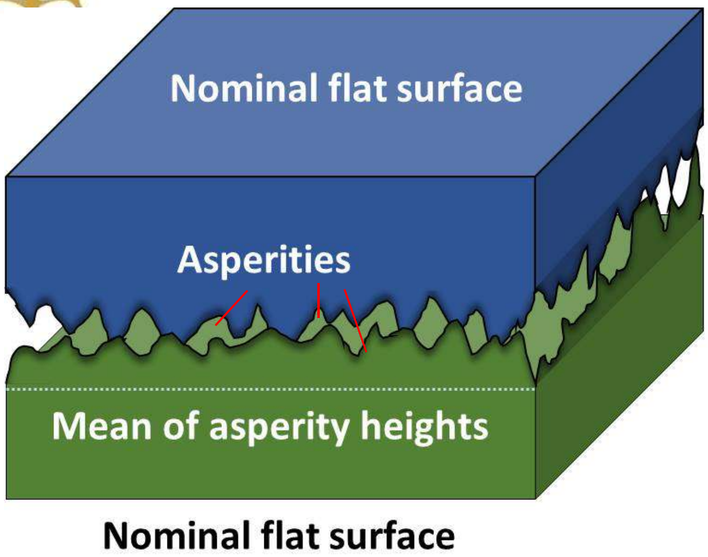
MK: Molykote (traditional lubrication)

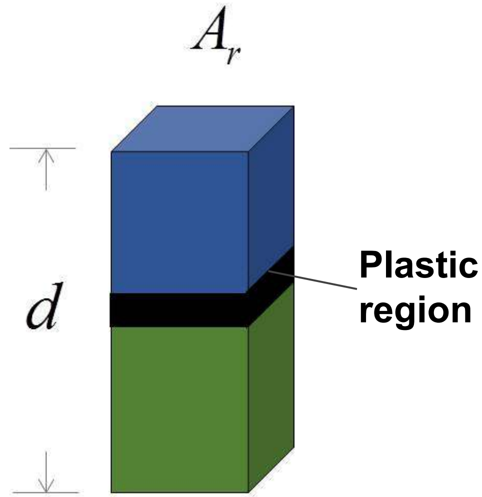
Both: Combined lubrication

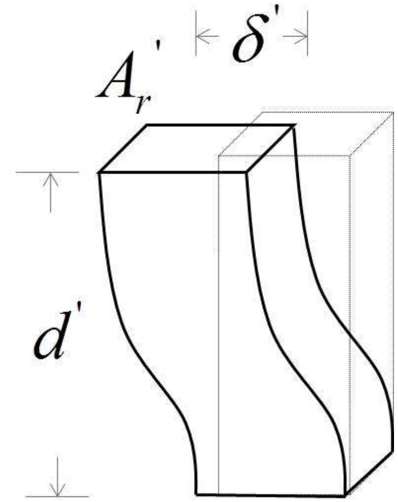
- US lubrication depends on velocity but not load; MK depends on load but not velocity; Both combined are mostly invariant with changing velocity or load
- **Region I**: Use US lubrication
- **Region II and III**: Use MK or MK + US depending on load
- **Region III**: Avoid US lubrication alone or increase US power

Electric power for US lubrication: 5.31 W

Cube Model







- The contact between two nominally flat surfaces in fact takes place between asperities

- A cube is used to represent the combined asperities. The height of the cube represents the average height of all the contacting asperities. The area of the top surface of the cube is equal to the actual contact area of two surfaces, which is much smaller than the nominal contact area

- The model takes plastic deformation of asperities into consideration

$$F_t = K_t \delta$$

(K_t is the contact stiffness, δ is the deformation)

$$K_t = \frac{E^* A_r^2}{d^3}$$

$$\delta' = \delta + u_1$$

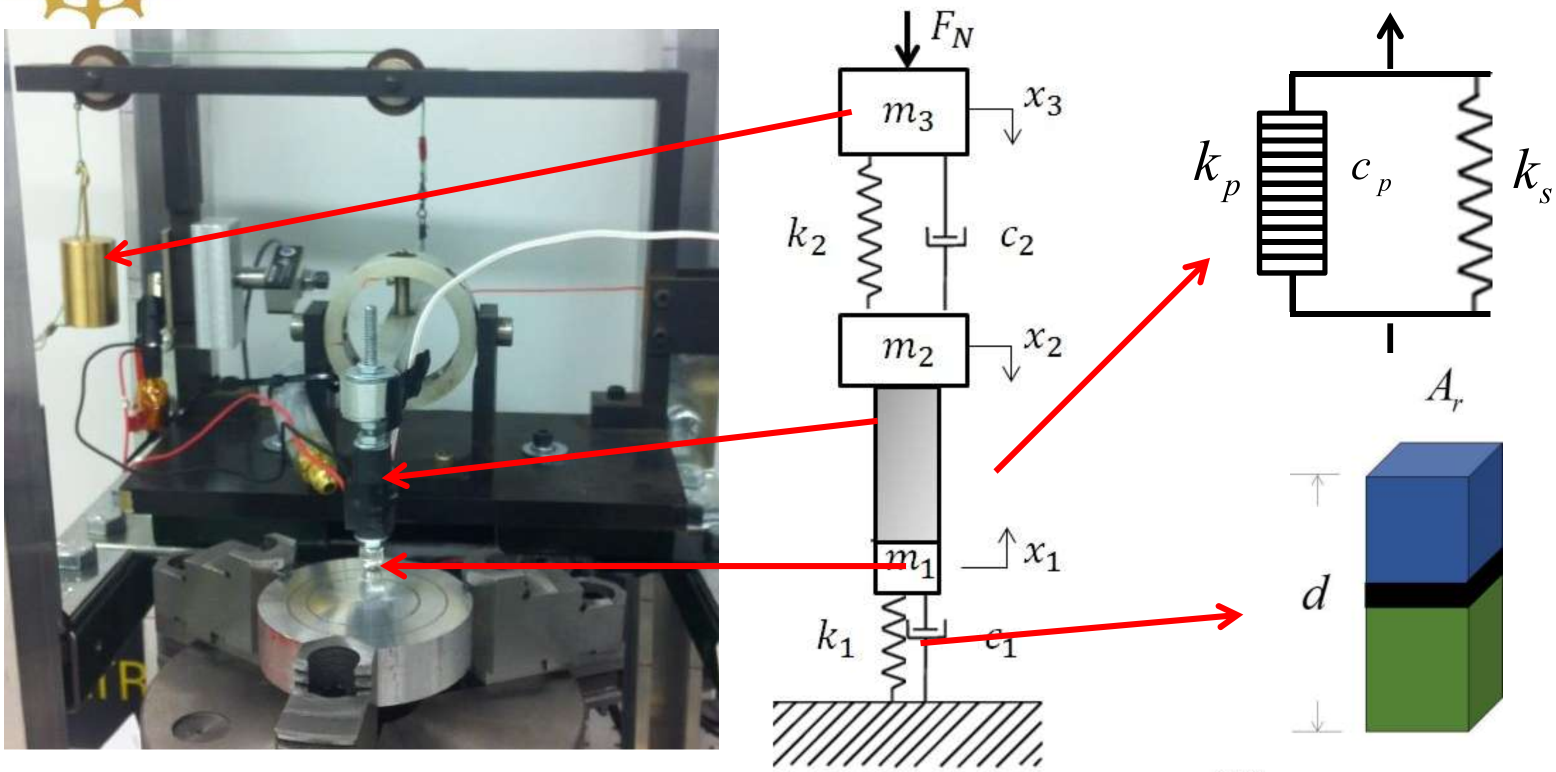
$$d' = d + u_3$$

(u_1 and u_3 are the relative displacements in longitudinal and vertical directions, respectively)

$$K_t' = \frac{E^* A_r'^2}{d'^3}$$

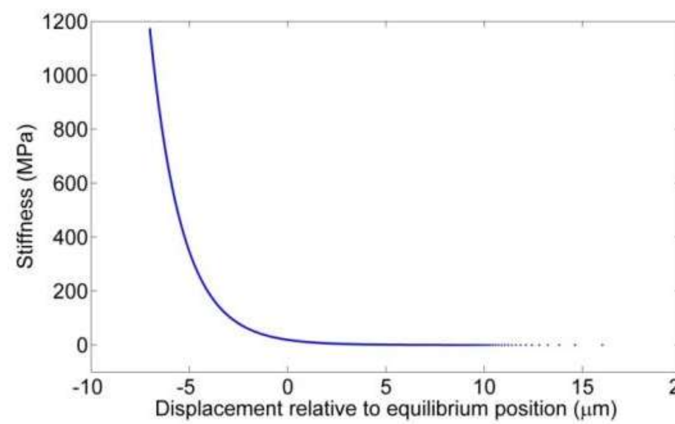
$$F_t' = K_t' \delta'$$

* Prime symbol denotes the value of parameters with ultrasonic vibrations



$$k_p^* = k_p + k_s$$

$$k_1 = \frac{E^* A_r}{d}$$



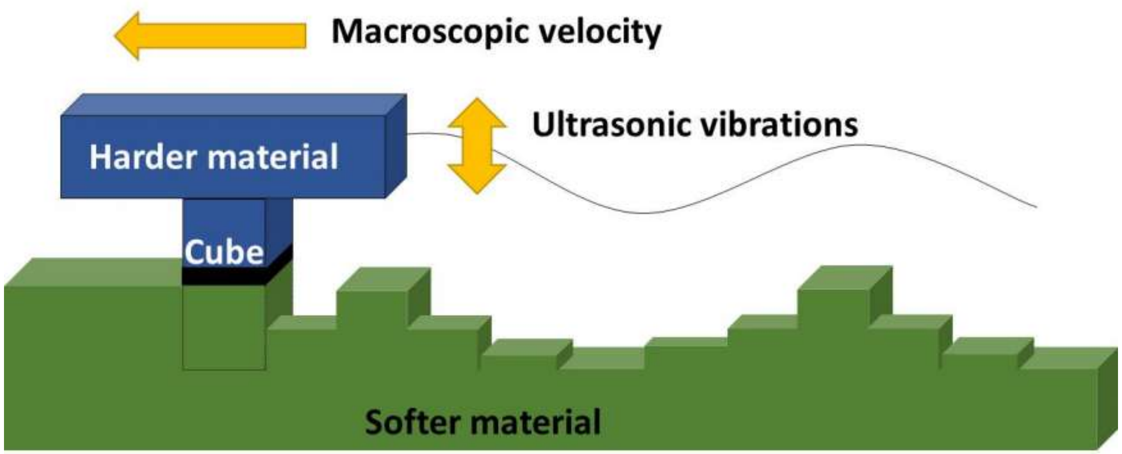
Spring k_1 represents the stiffness of the contacting asperities.

It works when the displacement is within a certain range around equilibrium, and it has non-linear behavior.

The relationship is calculated from the “cube” model.

Cube Model for Wear Reduction

Assumptions:
- Abrasive wear
- Cube model for the real contact between two surfaces
- Half of the volume of the cube is from the softer material
- The softer material gets removed



Total volume of the removed material in a cube can be calculated as

$$V = \frac{A_r d}{2}$$

where A_r is the real contact area and d is the height of the cube. When ultrasonic vibrations are applied, the volume of removed material is

$$V' = \frac{1}{2T}\int_0^T A_r' d' dt$$

The cube model is able to match the experimental data of friction and wear reduction with errors less than 15%.

Concluding Remarks

- Friction and wear reduction were investigated between various material combinations with conditions of various normal stresses and linear velocities

- Friction near 100% can be achieved under certain conditions

- Higher velocity results in lower friction reduction; normal stress has little effect on friction reduction

- Contour plots of power consumption, linear velocity, normal stress, and friction reduction were created from the experimental data

- A comparison between ultrasonic, traditional, and combined lubrication methods was conducted

- A cube model was proposed to explain and quantify ultrasonic friction and wear reduction

Thank you!

Additional Slides

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