Computational Contact Mechanics

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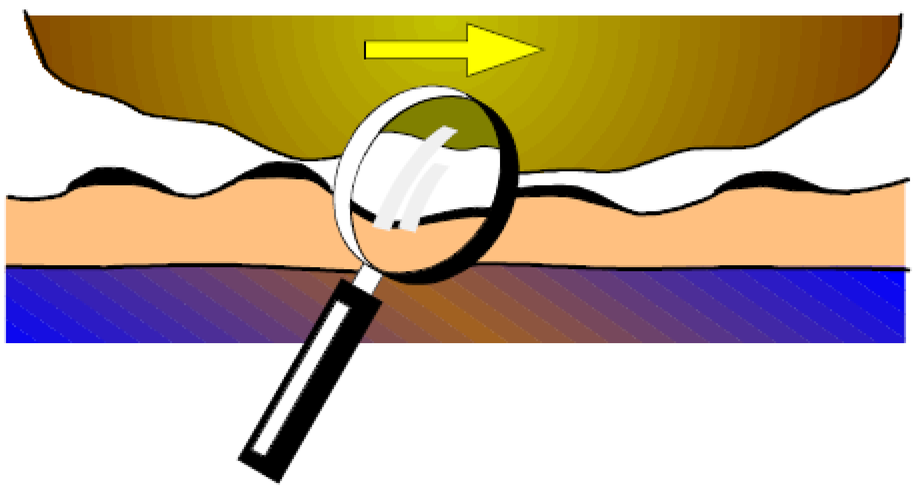
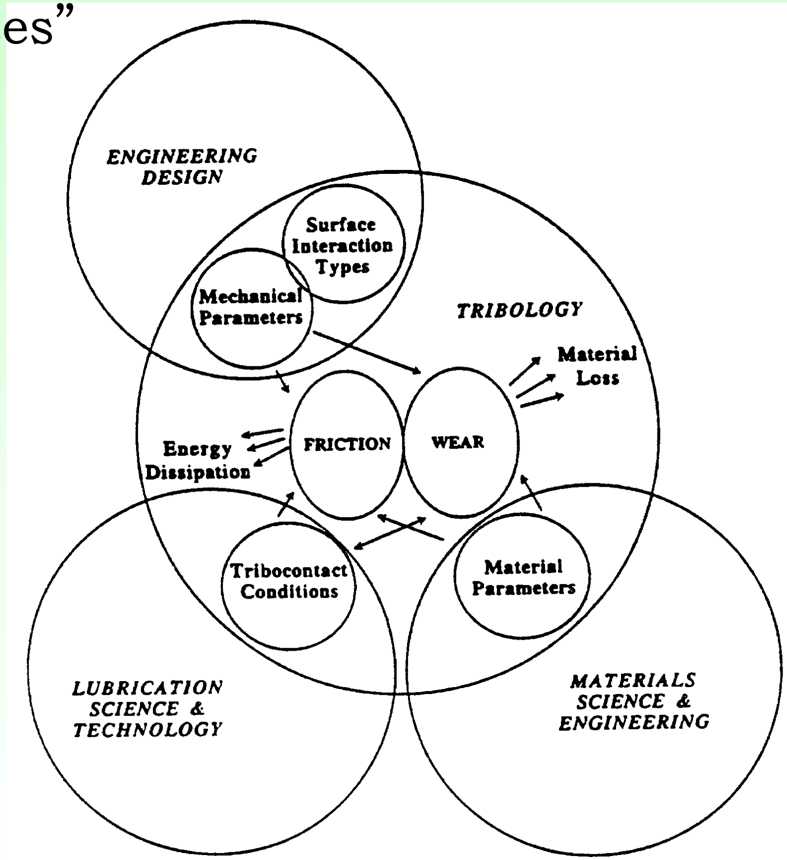
Tribology?

"The science of interacting surfaces in relative motion including its related practices"

Dept. of Education & Science, 1966





Tribology

- Two bodies in relative motion
- Results

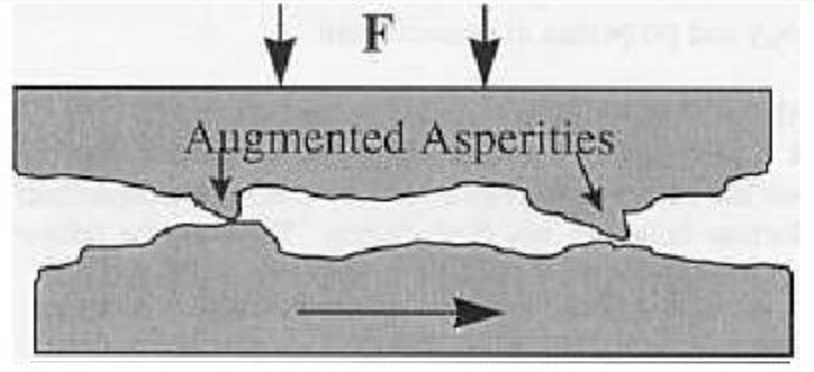
  - ✓ Friction
    - o Static friction
    - o Frictional heat, resistance against movement (friction force), loss of energy.
  - ✓ Wear
    - o Material loss degradation of surface, decreasing functionality.

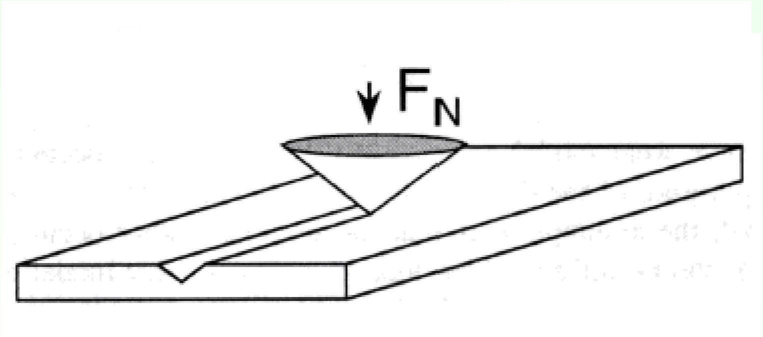
Friction is affected by..

- Presence of wear particles and externally introduced particles at the sliding interface
- Relative hardness of the materials in contact
- Externally applied load and/or displacement
- Environmental conditions such as temperature and lubricants
- Surface topography
- Microstructure or morphology of materials
- Apparent contact area
- Kinematics of the surfaces in contact (i.e., the direction and the magnitude of the relative motion between the surfaces)

Wear Mechanisms

- Adhesive
  - Low contact pressures
  - Augmented asperities
- Abrasive
  - High contact pressures
  - Wear tracks

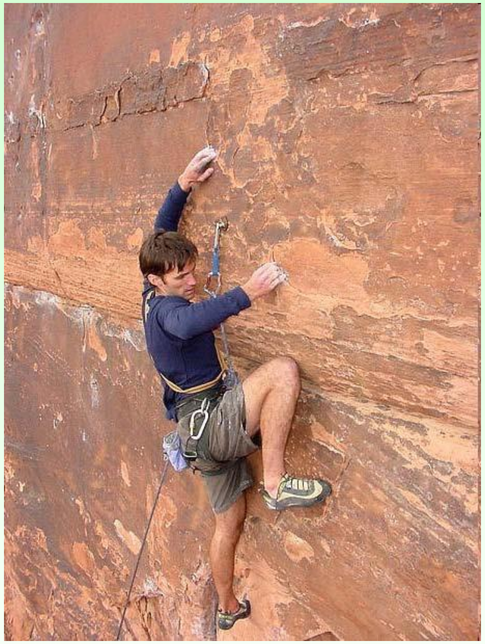




Friction in Every-day Life

Friction makes it possible

- To walk
- Use wheeled vehicles
- Sit
- Hold books



Tribology in Biological Science

- Wear of dentures
- Friction of skin and gaments, affecting the comfort of clothes, socks and shoes
- Tribology of contact lenses
- Wear replacement of heart values
- Wear of screws and plates in bone fracture
- Tribology of natural synovial joints and artificial replacements

“Tools” of the Trade

Tribological Assessment

- ***Material Parameters:***
  - Chemistry, Composition
- ***Operational Parameters:***
  - Load, Motion, Temperature, Duration
- ***Tribocontact Conditions:***
  - Contact mechanics, Lubrication mode, Surface topography
- ***Mechanical Parameters:***
  - Modulus, Hardness, etc.
- ***Friction & Wear Parameters:***
  - Friction coefficient, Wear factor, Wear mechanism

Surface Topography and Contacts

- Roughness, waviness, etc.
- Important in well lubricated interfaces with little wear
- Manufacturing operations – acceptable quality of machined surfaces
- Not important when wear takes place or when particles are present
- Surface must be designed to achieve certain functional requirements

Friction
- at what scale????

Friction at Nano- and Micro-scale Contacts

- Important in hard disk
- Nanoscale contacts

  ~ 10 nm

  Interatomic forces

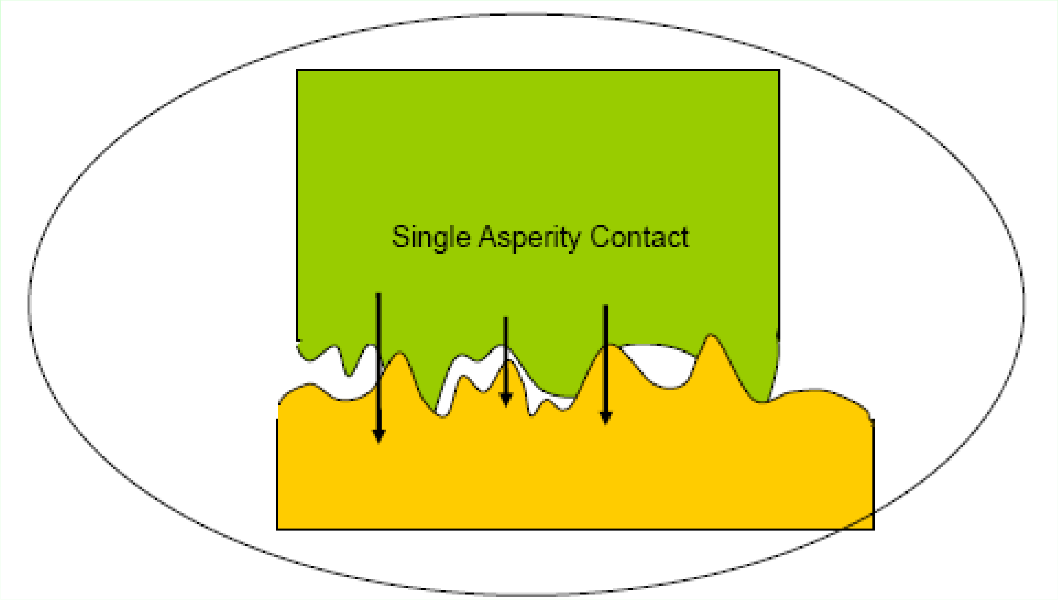
  $\mu \sim 0.07$
- Microscale

  ~ 10 nm

  $\mu \sim 0.7$ to 1

  Surface energy, meniscus and adhesion at the interface

Friction at Microscopic level



How do we measure friction?

- Macroscale Friction Test

  Friction tester under constant normal load

- Microscale and Nanoscale Friction test

  Atomic force microscope (AFM)

  Scanning probe microscope (SPM) etc.

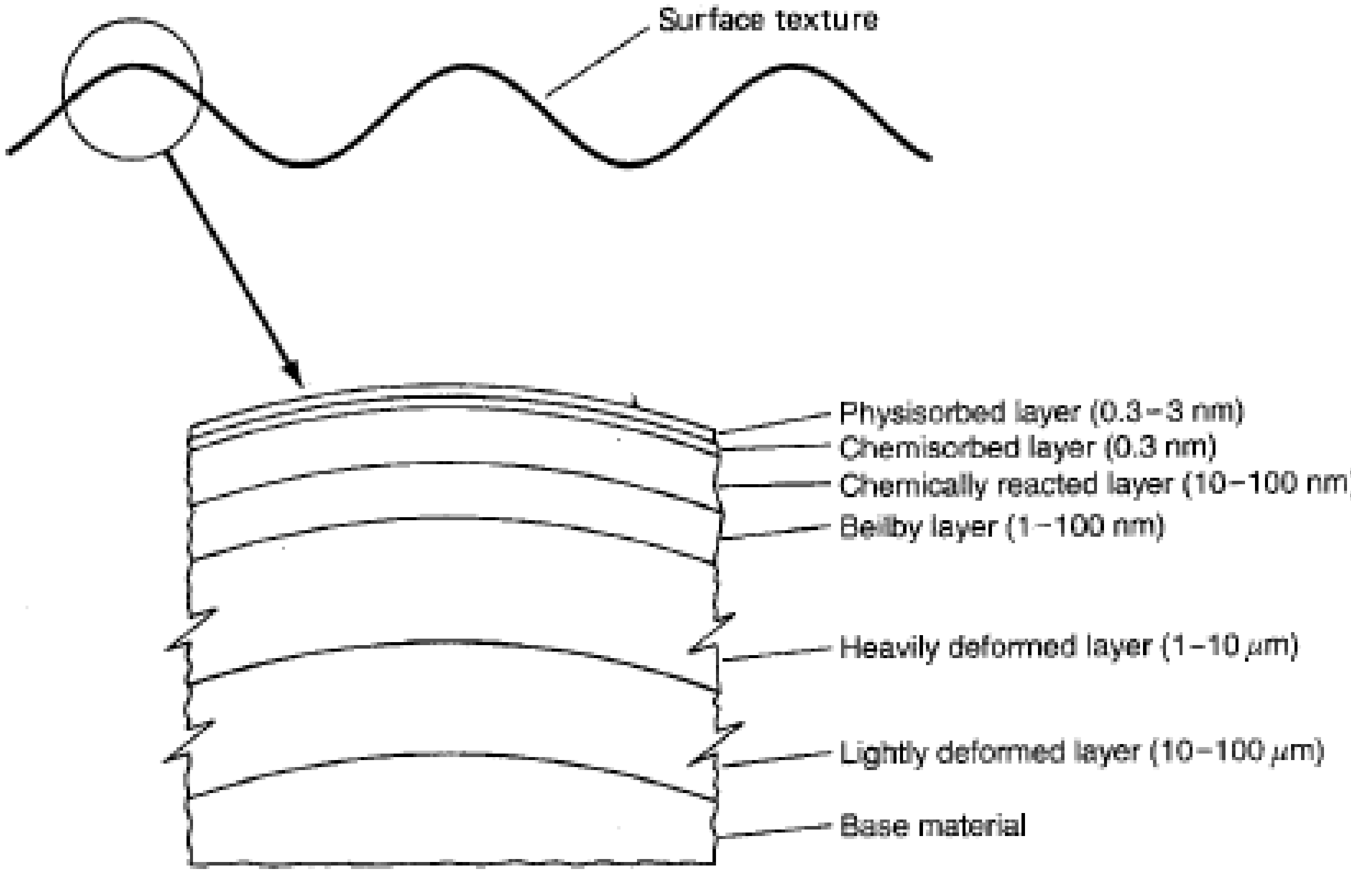
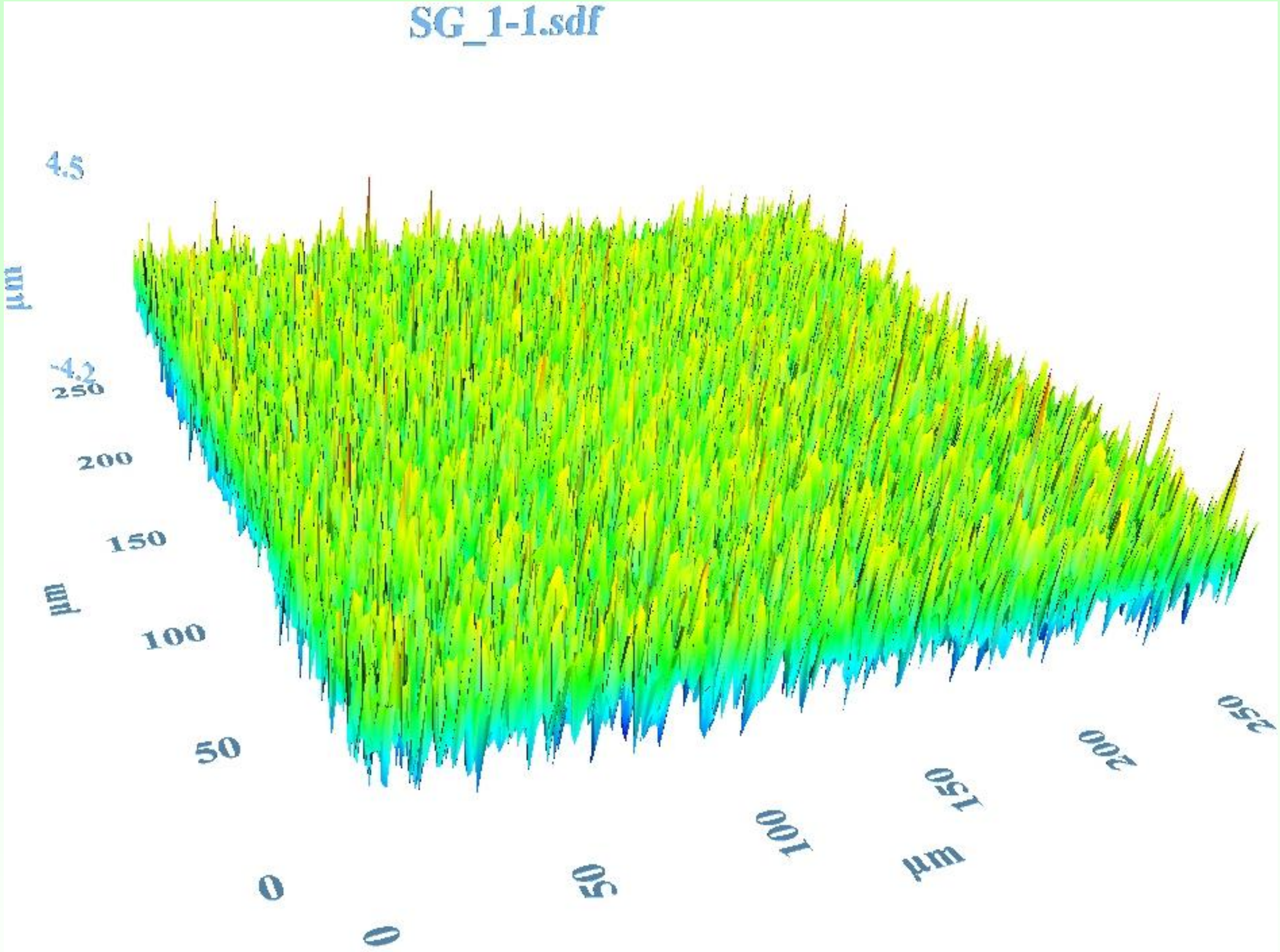


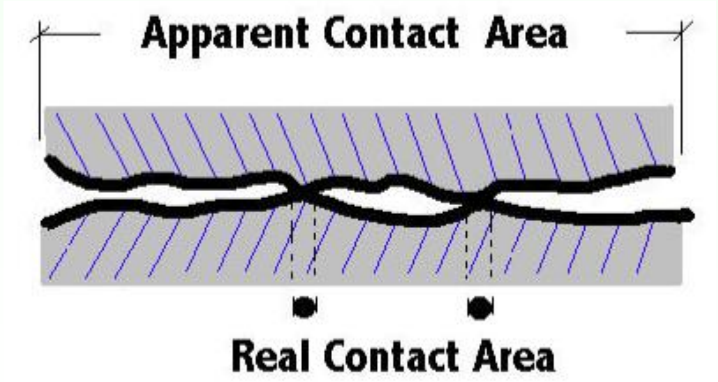
FIGURE 2.1 Solid surface details: surface texture (vertical axis magnified) and typical surface layers.

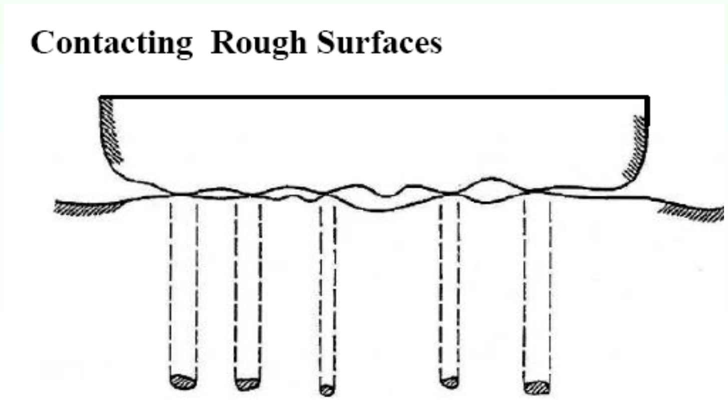

SG_1-1.sdf
4.5
μm
-4.2
250
200
150
μm
100
50
0
0
50
100
150
μm
200
250

Introduction

- **Contact Mechanics** studies (importance)
  - ✓ Contact interaction leads to friction and wear
  - ✓ as contact could not be avoided, the consequences of contact are to be minimized
  - ✓ a knowledge of the state of stress and strain among the bodies in contact is needed for this
- Deeper understanding of tribological process are now being attempted to be achieved by using modeling and simulation.
- **Finite Element Method** is playing an increased role in this aspect
- Macroscopic simulation of contacting bodies leads to a full visualization of the happenings in the contact zones.
- **Wear** is the progressive loss of material from a surface due to relative motion mainly at the contacts
- Modeling and analysis of wear depend on relating the (surface) parameters to the contact consequences.

- Conformal Surface :- contact of a few asperities
- **Real area of contact** is small fraction of apparent area of contact.
- When two flat surfaces are in contact – sum of the areas of all contact spots constitutes real area of contact.
- Friction and wear depends upon the nature of contact and size of the real contact area between the two surfaces.
- The modeling of surface asperities on the micro-scale is of great interest to those interested in the mechanics of surface contact, friction and wear.
- As the mechanisms originate at the **asperity** level, research attempts are made to capture the influence of asperity deformation





Classical Contact Mechanics

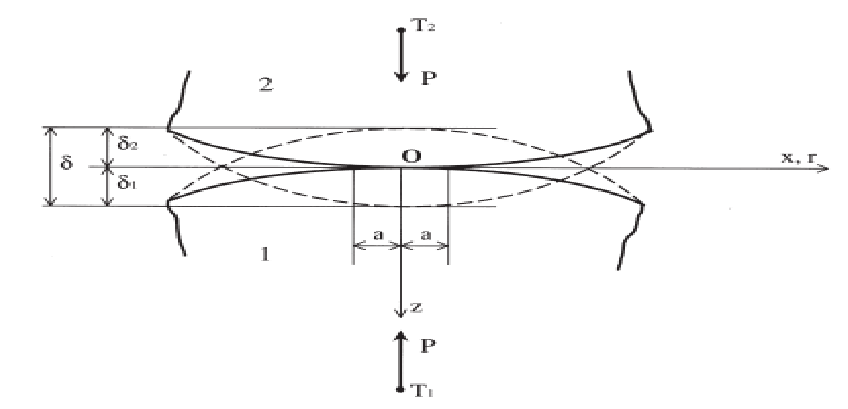
Hertz (1882),analyzed the stresses in the contact of two elastic bodies.

Assumptions

1. the surfaces are elastic, homogeneous and isotropic
2. the strains are small
3. the surfaces are smooth and non-conforming
4. the surface does not change in time and
5. the surface are frictionless.

$$a = \left(\frac{3PR^*}{4E^*} \right)^{1/3}$$

$$\delta = \left(\frac{9P^2}{16R^* E^{*2}} \right)^{1/3}$$



$$p_o = \left(\frac{6PE^{*2}}{\pi^3 R^{*2}} \right)^{1/3}$$

$$\frac{1}{E^*} = \frac{1-\gamma_1^2}{E_1} + \frac{1-\gamma_2^2}{E_2}$$

$$P_c = \frac{21.17 R^{*2} Y^3}{E^{*2}}$$

$$\delta_c = \frac{6.32 R^* Y^2}{E^{*2}}$$

$$\frac{1}{R^*} = \frac{1}{R_1} + \frac{1}{R_2}$$

Rough Surface Contact Models

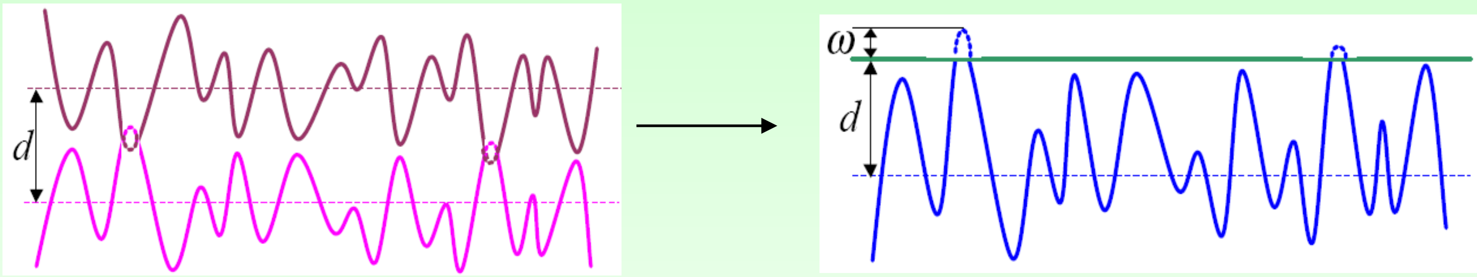
- **Statistical methods -** Model surface as a statistical distribution of asperities with various heights and properties (Computationally inexpensive and easier to approach)
- **Deterministic methods -** Model the real features of the surface as with much detail as possible (Computationally expensive and difficult)
- **FFT methods -** Problem solved in Frequency domain
- **Fractal methods -** Multiple scale roughness is considered

Using Statistical methods:

- May think deterministic models give accurate results
- Here to model single asperity mostly more than 10,000 elements in the FEM analysis, requires huge computational time!
- While in deterministic models with entire surface may contains n number of asperities with different radius and heights

Literatures

- The contact of two rough surfaces is initially modeled by an equivalent single rough surface contacting a rigid smooth plane (**Greenwood and Williamson**, 1966) (GW model) and (**Greenwood and Tripp**, 1971)
- The model is based on classical Hertz solution for single asperity.



GW model assumptions

- ✓ The rough surface is isotropic.
- ✓ Asperities are spherical near their summits.
- ✓ All asperity summits have the same radius of curvature, *R*, but their heights vary randomly.
- ✓ Asperities are far apart and there is no interaction between them.
- ✓ There is no bulk deformation. Only the asperities deform during contact.

Motivation

KE model concludes

- Plastic region develops below the surface when $\omega/\omega_c<6$, and fully plastic region starts after $\omega/\omega_c>68$
- p/Y reaches 2.8 when ω/ω_c is 110
- Results can be used for all elastic plastic cases

JG model concludes

- Fully Plastic region starts when ω/ω_c is in between 70 to 80, but considered only three yield strength based on the shrinkage of the elastic core.
- Effect of strain hardening is not considered, but concludes as p/Y never reaches 2.8

	KE Model	**JG Model**
1	***Y*** **variation not considered**	***Y*** **- Considered (up to 1619)**
2	**Effect of strain hardening is considered**	**Effect of strain hardening is not considered**
3.	***p/Y*** **reaches 2.8**	***p/Y*** **does not reach 2.8**

Objectives - Single Asperity Contact

- Finding Contact Parameters i.e., ***P*, *A* and *p*** in the elastic-plastic regime, as functions of ω for various yield strengths

- Evaluating the difference in the results from the previous models in elastic plastic regime, when ***Y* and E_t** are included

- Monitoring the development of the **elastic core** and the **plastic region** inside the surface

- Identifying the inception of fully plastic region for various ranges of yield strengths in elastic plastic regime

- Developing an unified empirical relation to determine the exact start of fully plastic regime when properties of the materials are included

- Calculating the contact parameters of rough surfaces using present single asperity contact model results

Present work

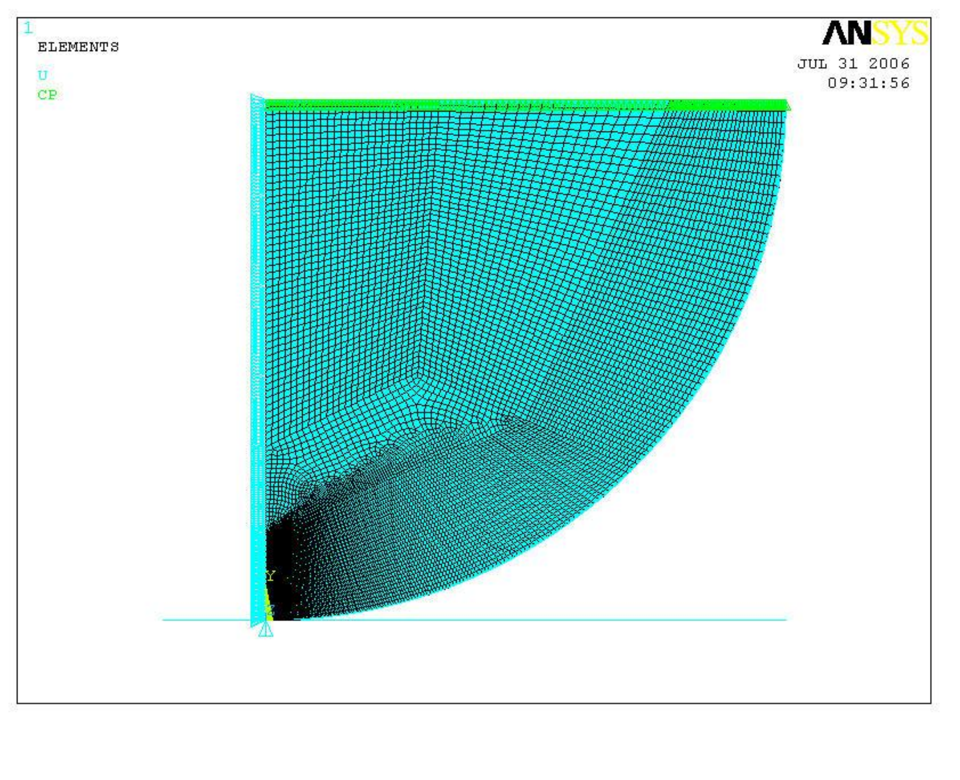
- Extends the KE and JG models for the single asperity contact
- Extended to maximum interference ratios (ω/ω_c>400)
- Solved for various yield strengths

Assumptions:

- Bilinear Isotropic Strain Hardening (BISO)
- Tangent modulus is assumed as zero, elastic perfectly plastic contact condition to meet with the KE and JG models.
- Yielding criterion: von Mises

***Material and Geometric Properties*:**

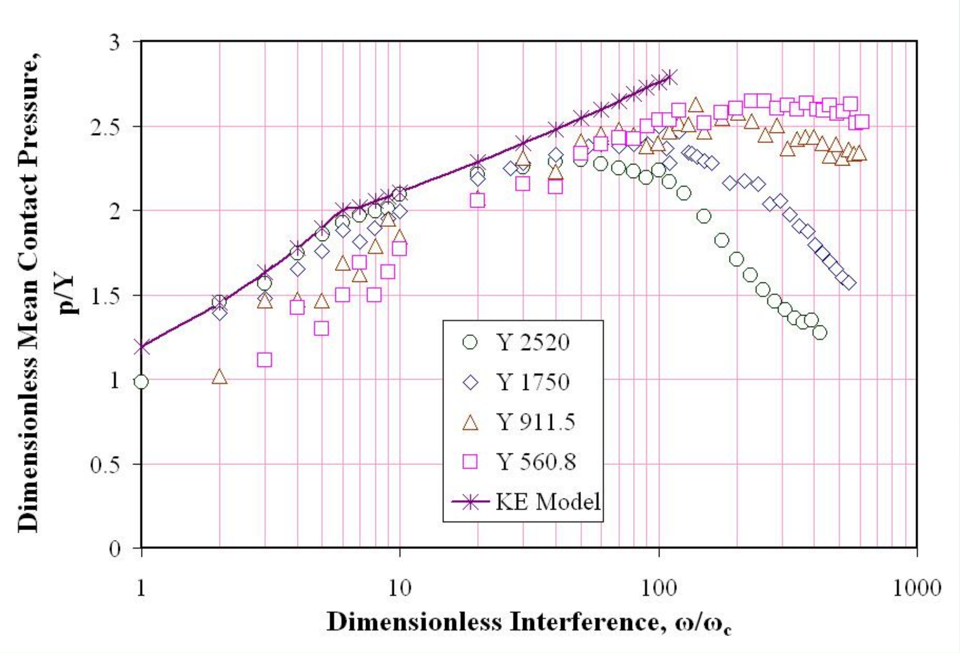
S.No	Parameters	Values
1	Young's Modulus E (N/mm^2)	$2.07*10^5$
2	Poisson's ratio γ	0.3
3	Yield Strength Y (N/mm^2)	250 to 2250



- Boundary Conditions
- Element Type
- Contact Conditions
- Loading methods

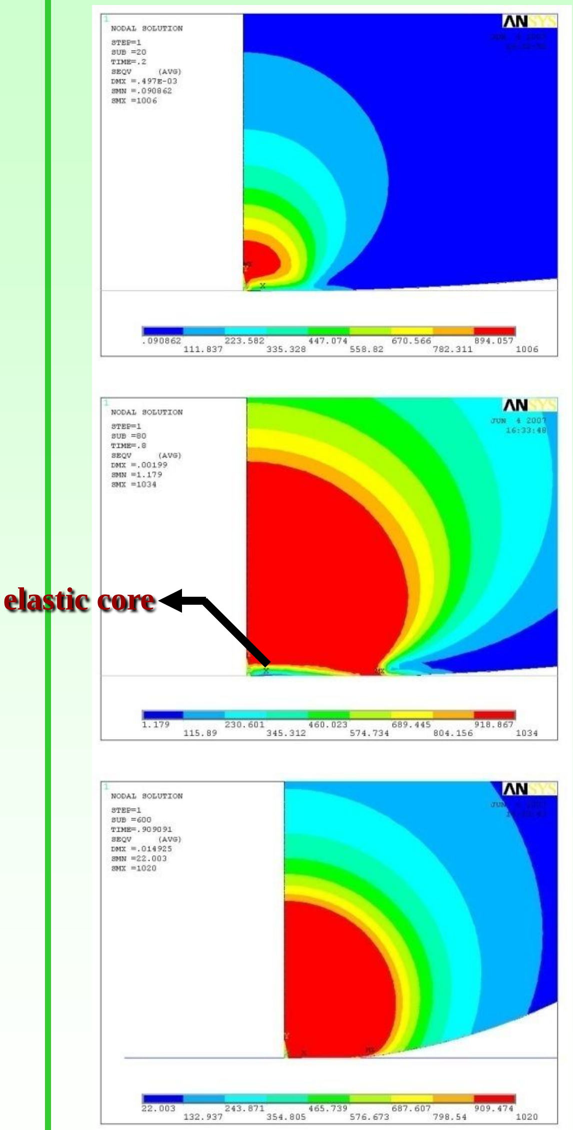
- Convergence check by varying the number of elements and step sizes.
- 9933 elements in total and varying up to 24510 elements
- 63 % of total elements lies along the circumferential region
- 47 % of which lies close to the contact region of the hemisphere
- Remaining 37% of the asperity are filled with coarse mesh.

Single Asperity Results-Elastic perfectly plastic case



- The contact becomes fully plastic when p = 2.8~3Y (***Tabor***)
- At Y 2520 N/mm^2, p/Y value reaches a maximum of 2.3
- For Y 560.8 N/mm^2, p/Y reaches a maximum of 2.6-2.7
- Prediction of the change in elastic plastic to fully plastic state using Tabor results is invalid for elastic perfectly plastic case contact conditions

Stress Distribution and Evolution



Elastic :

➢As the load is applied the plastic region is developed at the subsurface and occurs beneath the surface

Elastic Plastic :

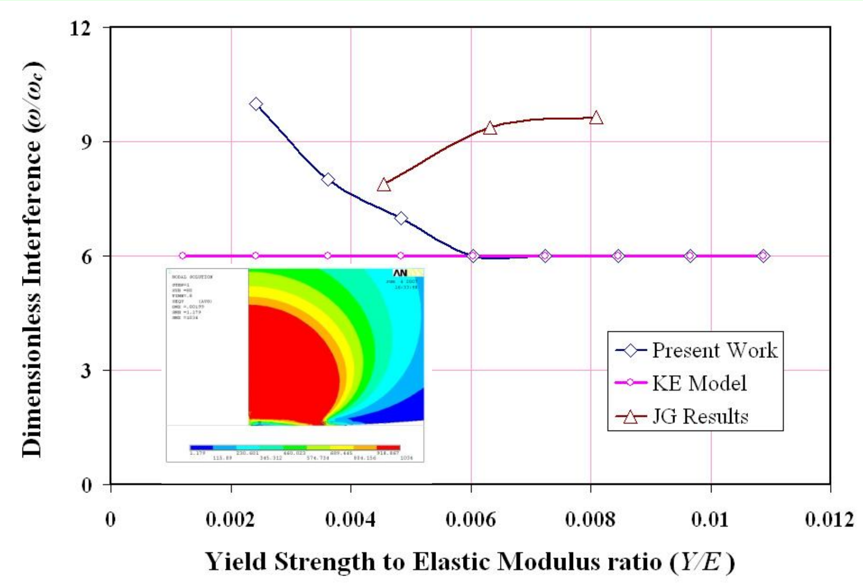
➢As ω increases, the plastic region first reaches the surface of the sphere, yielding will initiate

➢An elastic core is formed at the junction of the contacting region surrounded by the plastic region

Fully Plastic State:

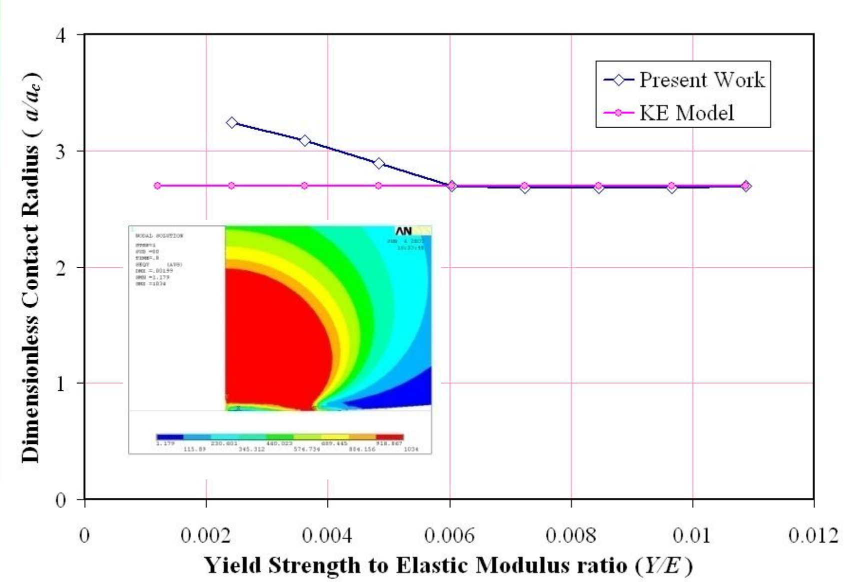
➢Further increasing the ω, the elastic core completely disappears and fully plastic region reaches the contact interface

Elastic Plastic Region based on the Elastic core



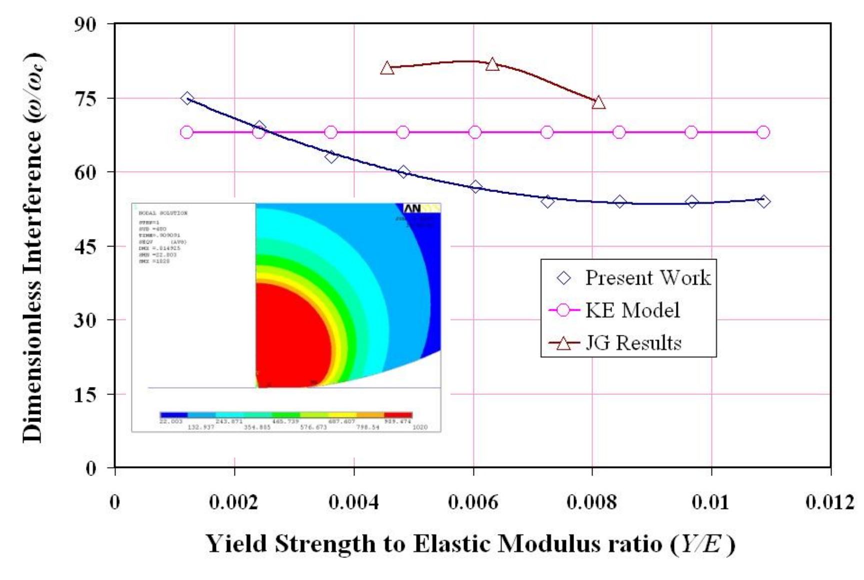
➢**KE model**, when ω/ω_c reaches 6, the elastic core is developed, then elastic plastic regime starts

➢**JG model**, elastic plastic regime starts when ω/ω_c is in between 7.89 to 9.64



➢**KE model**, the plastic region first reaches the sphere surface at $2.7a_c$

➢ Present model results varies from 3.24 a_c to 2.7 a_c.

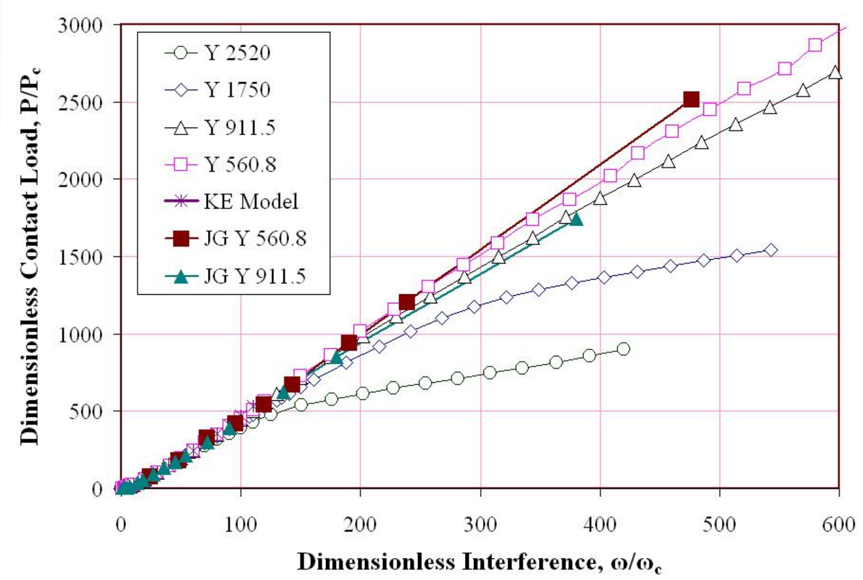


➢**KE model**, the elastic core shrinkage takes place at the specific ω/ω_c of 68

➢**JG Model**, the fully plastic interference seems to range in between 70 to 80

➢For lower *Y* values, P/P_c increases proportionally with the increase in ω/ω_c up to 110

➢The P/P_c stabilize after certain interference and shows a saturation for higher yield strengths



FEM predicted Contact Load and Contact Area

- **KE model** concentrate only on the *p/Y* value to determine the onset of fully plastic regime.
- *p/Y* value never attains a value of 2.8, so the analysis is extended for higher interference ratios
- FEM predicted contact area for different yield strength values correlate well with the **KE model** and **JG models** for the entire interference ratio

$$\omega/\omega_c \le 1, \textit{elastic}$$

$$1 < \frac{\omega}{\omega_c} < 10, \quad \frac{P}{P_c} = 1.0392\left(\frac{\omega}{\omega_c}\right)^{1.4111}$$

$$10 < \frac{\omega}{\omega_c} < 80, \quad \frac{P}{P_c} = 1.7035\left(\frac{\omega}{\omega_c}\right)^{1.202}$$

$$80 < \frac{\omega}{\omega_c} < 150, \quad \frac{P}{P_c} = 8.1242\left(\frac{\omega}{\omega_c}\right)^{0.8402}$$

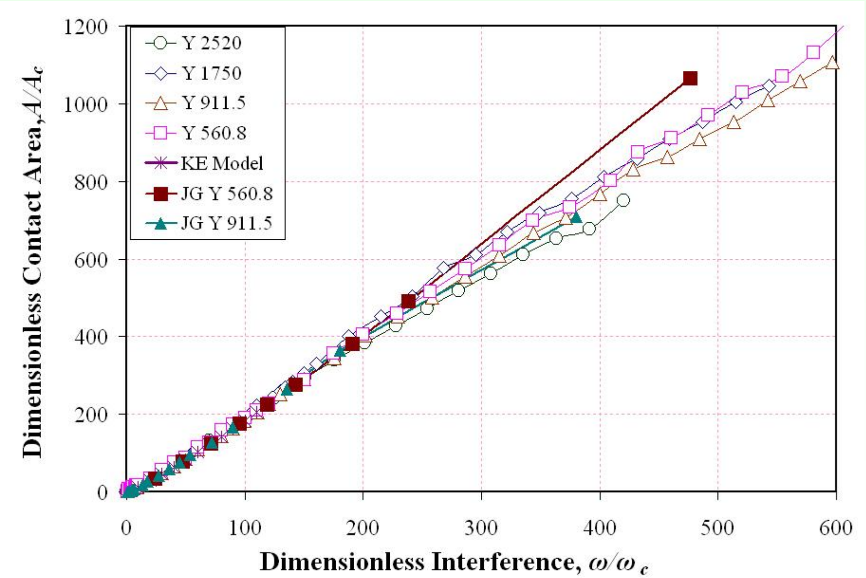
$$150 < \frac{\omega}{\omega_c} < 450, \quad \frac{P}{P_c} = 46.165\left(\frac{\omega}{\omega_c}\right)^{0.4873}$$

$$\omega/\omega_c \le 1, \textit{elastic}$$

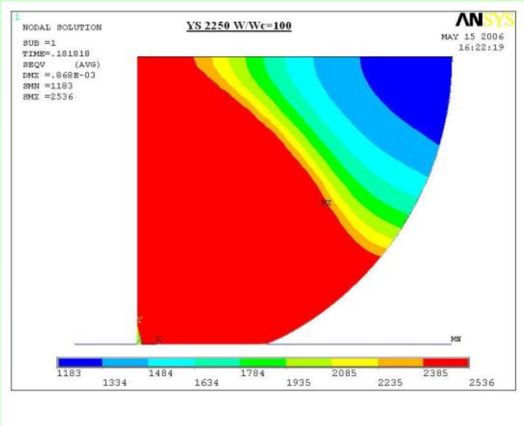
$$1 < \frac{\omega}{\omega_c} < 80, \quad \frac{A}{A_c} = 0.9568\left(\frac{\omega}{\omega_c}\right)^{1.1547}$$

$$80 < \frac{\omega}{\omega_c} < 150, \quad \frac{A}{A_c} = 1.6077\left(\frac{\omega}{\omega_c}\right)^{1.0373}$$

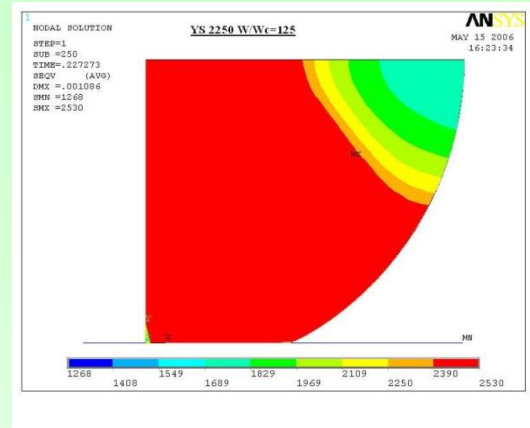
$$150 < \frac{\omega}{\omega_c} < 450, \quad \frac{A}{A_c} = 3.1823\left(\frac{\omega}{\omega_c}\right)^{0.9026}$$



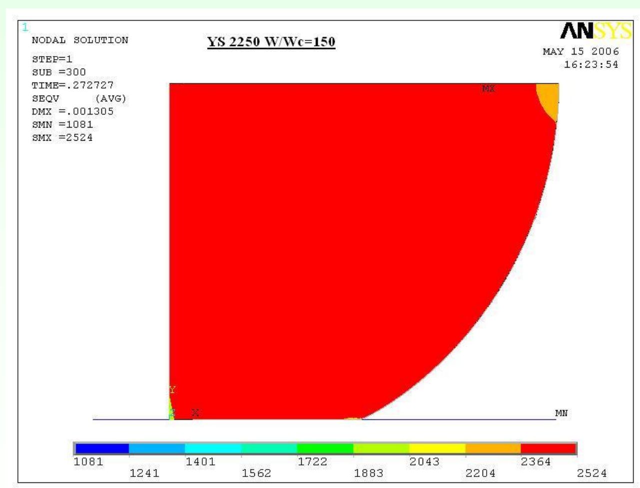
Yield Strength 2520 N/mm²



$$\frac{\omega}{\omega_c} = 100$$

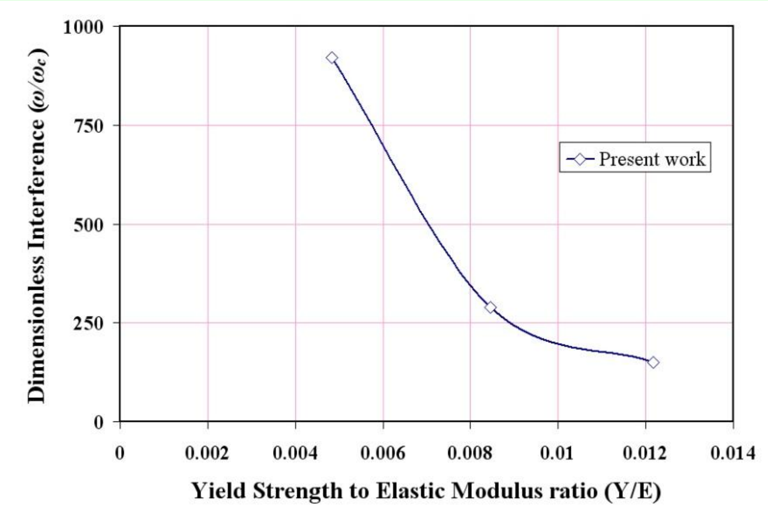


$$\frac{\omega}{\omega_c} = 125$$



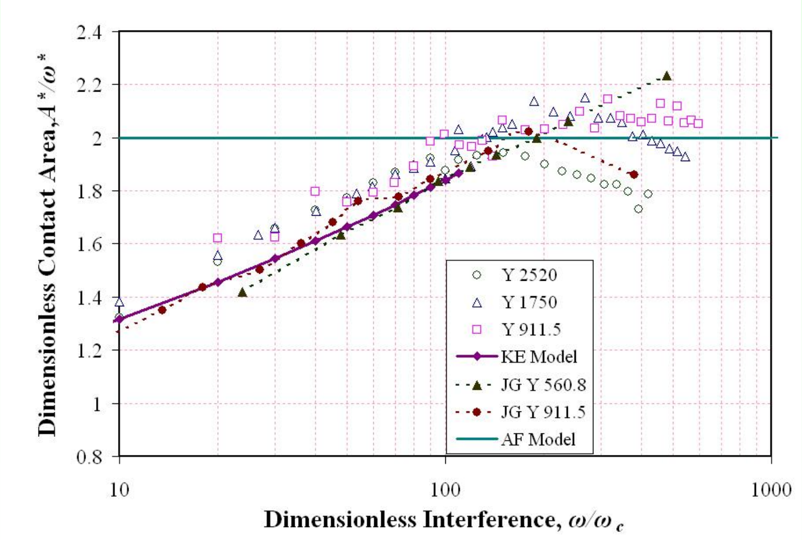
$$\frac{\omega}{\omega_c} = 150$$

Plastic region fully dominates over the hemisphere surface

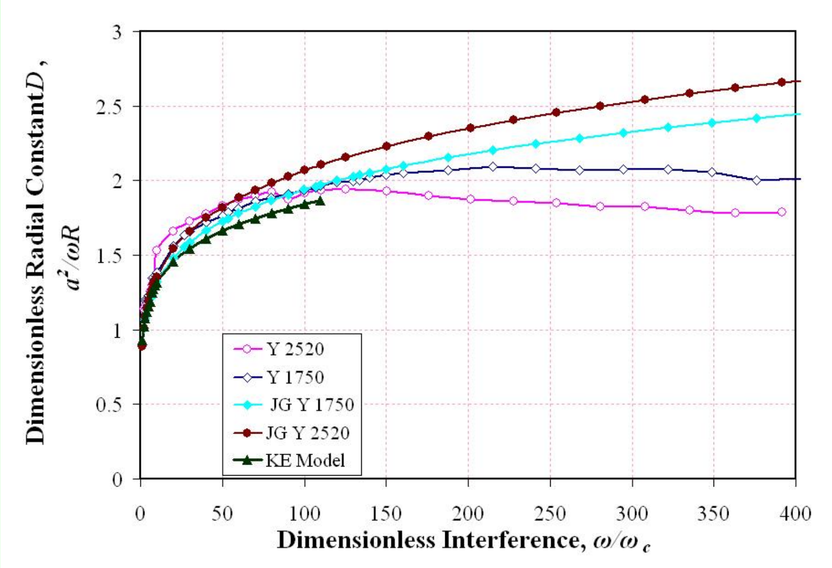


- For *Y/E*<0.06, the ω/ω_c required is more than 750
- Higher *Y/E* ratios, the required ω/ω_c gradually reduces and it is less than 250

- **AF model**, A^*/ω^* crossing 2, the material reaches fully plastic state
- This decreasing trend occurs before (A*/ ω*) is 2
- For lower yields A*/ω* crosses 2, but for higher Y ratios , the trend reverses



Variation of mean contact pressure ratio with contact radius ratio



➢The contact load saturation begins at the ω/ω_c of 150 for the *Y* 2520 N/mm², at that stage the *a/R* value is nearly 0.4685

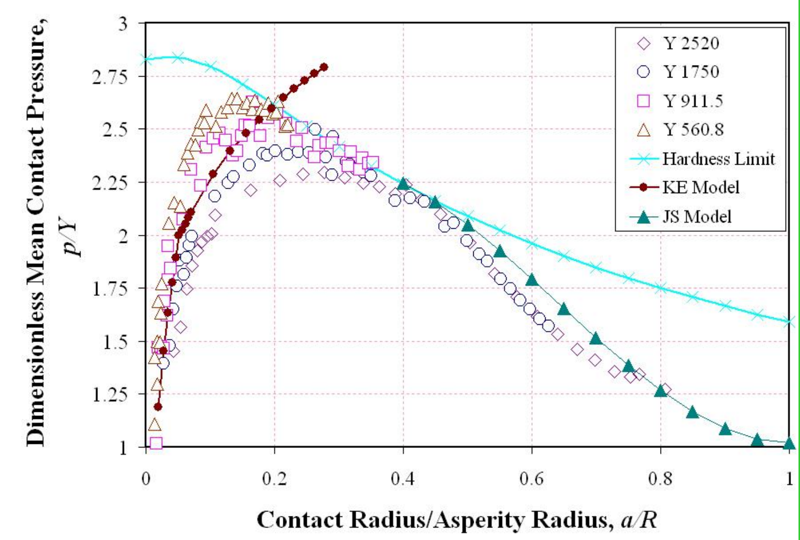
➢At ω/ω_c 110, a/R is 0.41 for *Y* 2520 N/mm², but the difference is very high

➢For lower *Y* values, the peak *p/Y* value is reached at lower *a/R* ratio.

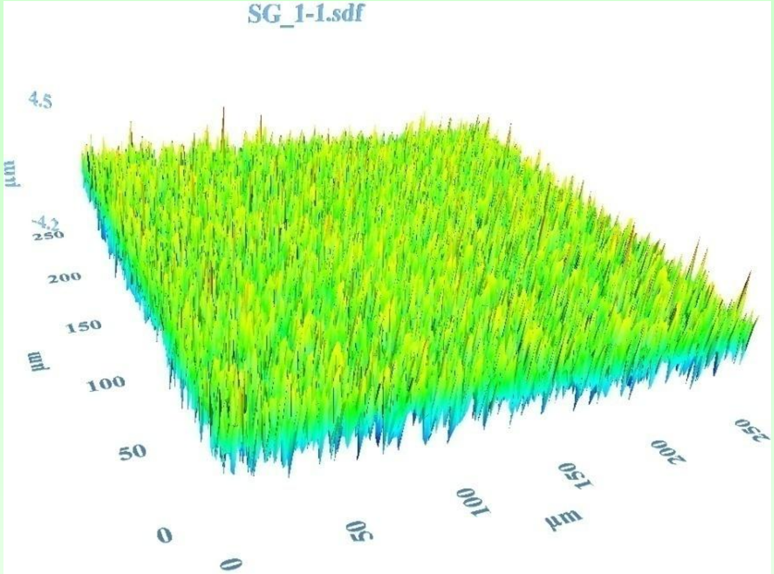
➢When *Y* increases, the peak *p/Y* decreases and the *a/R* value at the peak *p/Y* increases for the same ω/ω_c.

➢For *Y* 560.8, 911.5, 1750 and 2520 N/mm², *a/R* ratio value - 0.41, their corresponding ω/ω_c is 700, 600, 240, and 110 .

➢This shows that by increasing *Y*, even at low ω/ω_c, *a/R* reaches 0.41

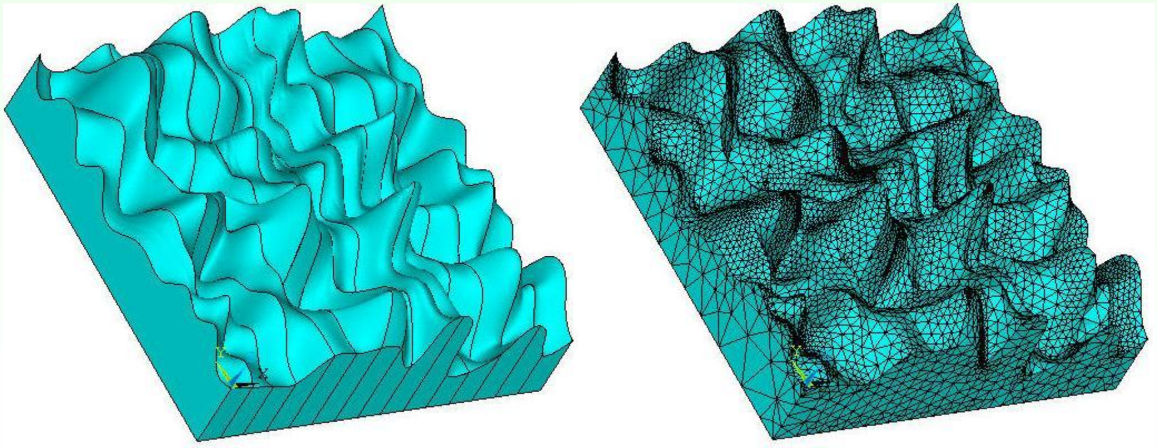


Statistical and Deterministic models

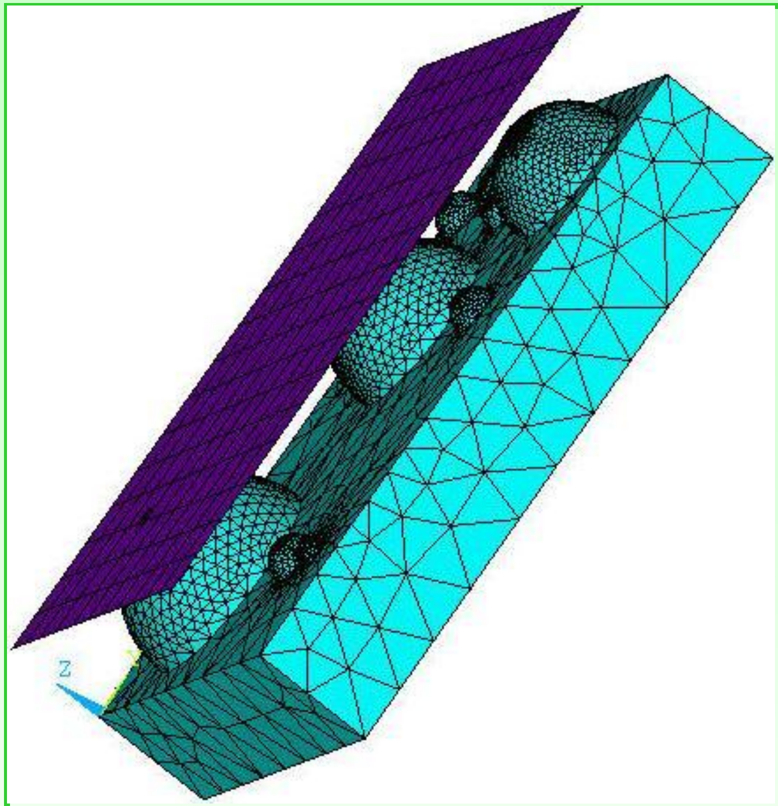


Real Engineering Surface

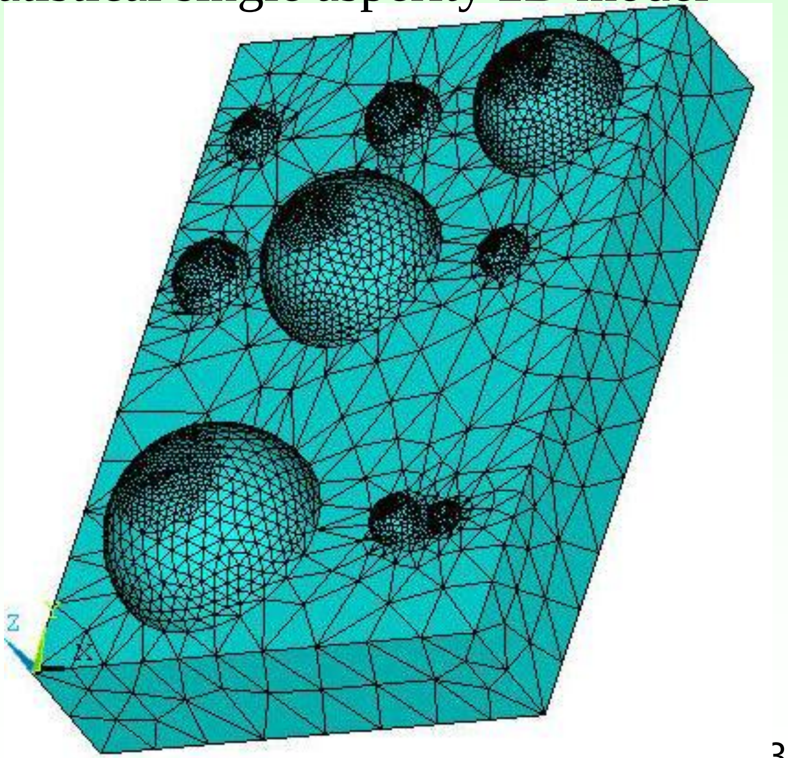
- Real surface is generated based on Son Bui et al. data's. (256*256)
- Randomized block of 16*16 is selected



Finite Element Randomized Deterministic model

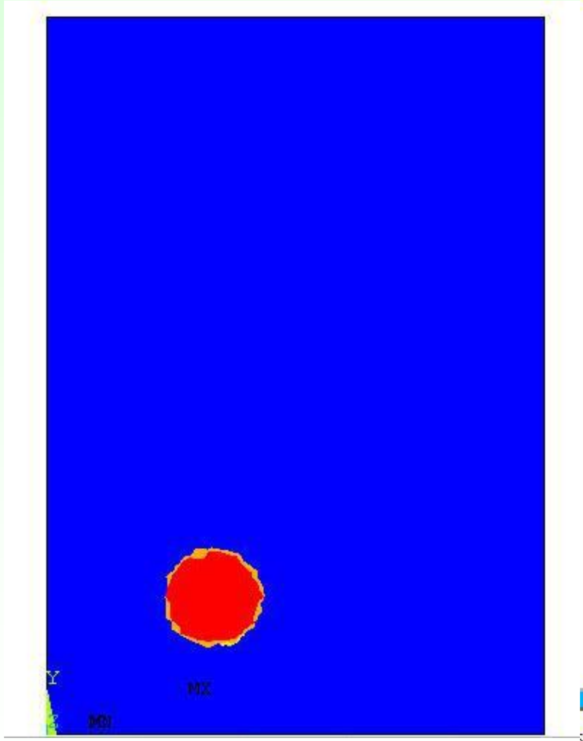


- A Reference plane is created below the surface
- Tips of the asperity is assumed to be spherical
- Height above the plane considered as asperity radius
- Comparing this 3D deterministic model with statistical single asperity 2D model

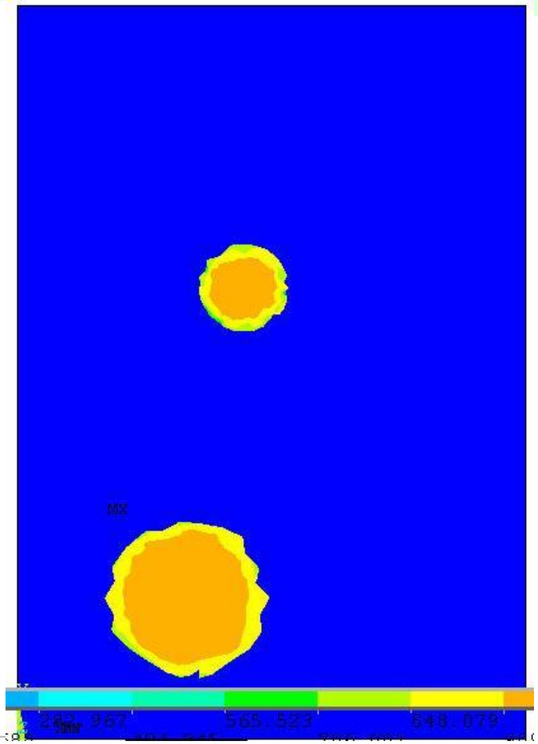


Real Contact Area for varying Interference

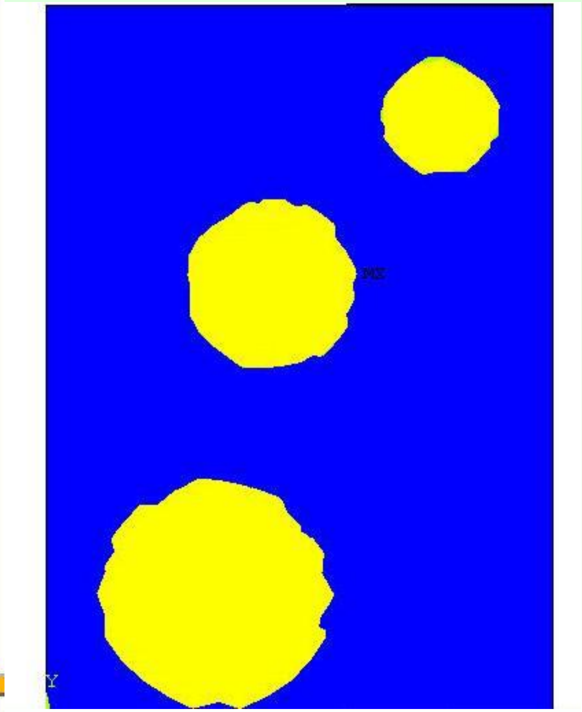
- Total interference of 0.5µm is applied over the rigid surface
- Resulting contact load, contact area are calculated
- Up to 0.15µm interference, only one asperity is in contact and neighboring asperity comes into picture when interference increases



0.1µm



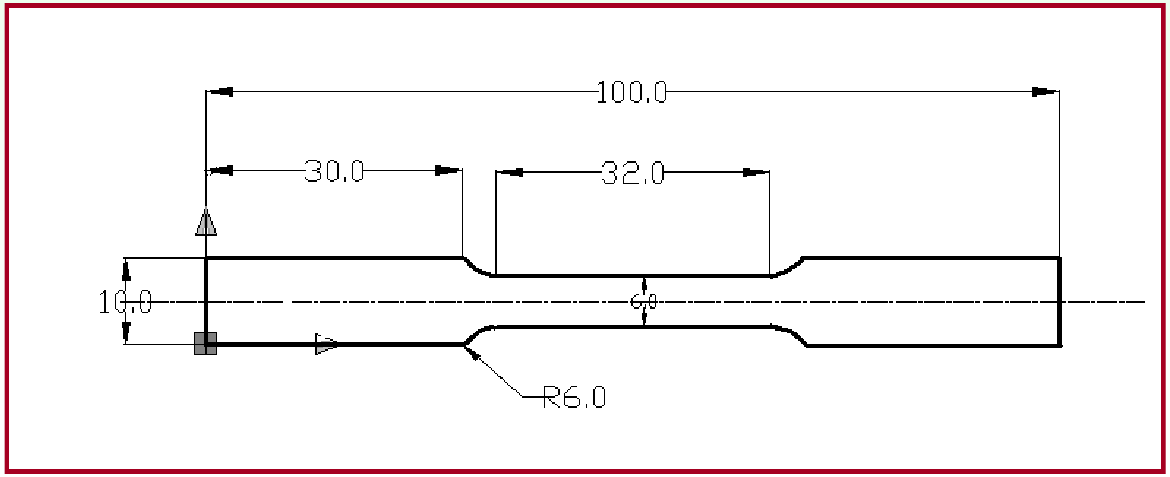
0.25µm



0.5µm

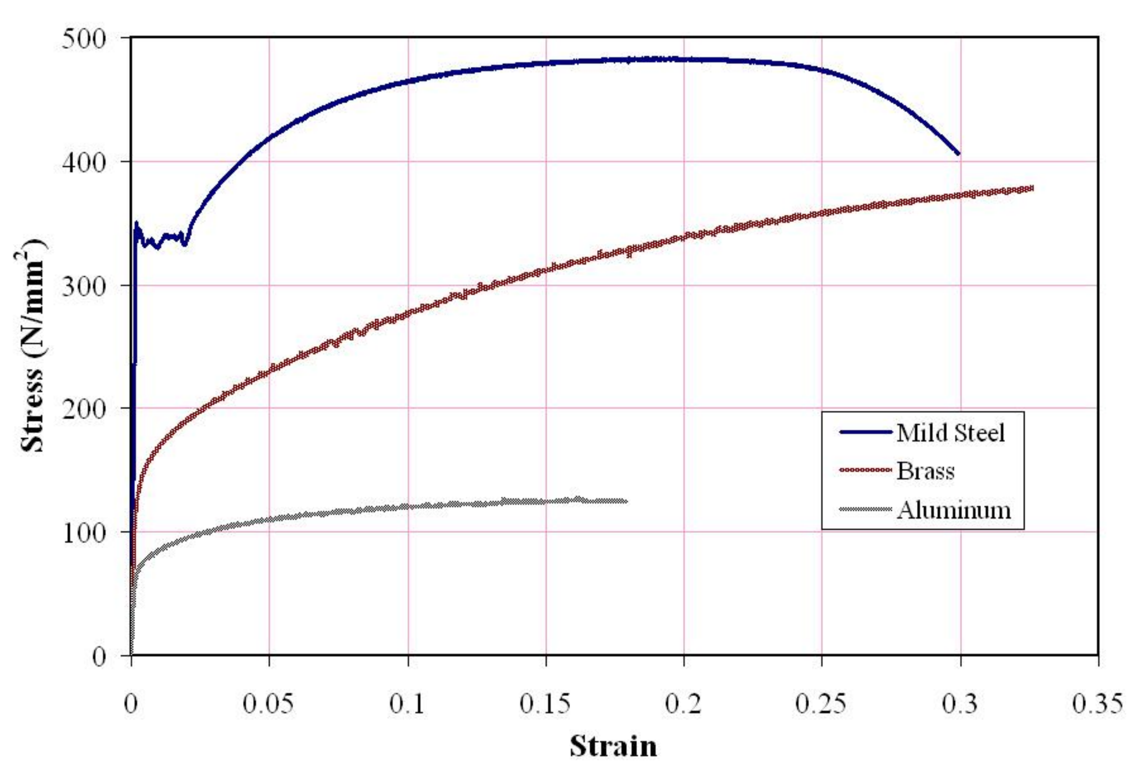
Experimental Approach

- To validate with the finite element results, hard ball on contact with the smooth flats (half space indented by a rigid sphere) were tested in macroscopic level for different loading conditions from elastic to fully plastic state.
- Flat specimens of three different materials Mild Steel, Brass and Aluminum were used.
- For obtaining the real material properties of the smooth flat specimens, standard tensile test method is carried out.
- The tensile test specimen is prepared as per ASTM E8M standards and the test is performed in available material testing system facility



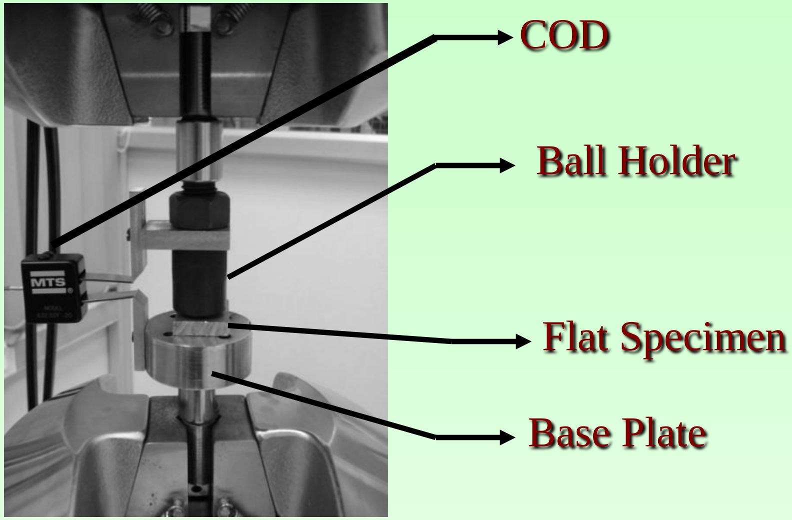
Standard tensile specimen

Stress-strain Curve



Properties	Mild Steel	Brass	Aluminum
Young's modulus (N/mm^2)	$2.37*10^5$	$1.13*10^5$	$0.70*10^5$
Poisson's ratio	0.3	0.33	0.33
Yield Strength (N/mm^2)	340.73	138.9	71.369

Ball Indentation test



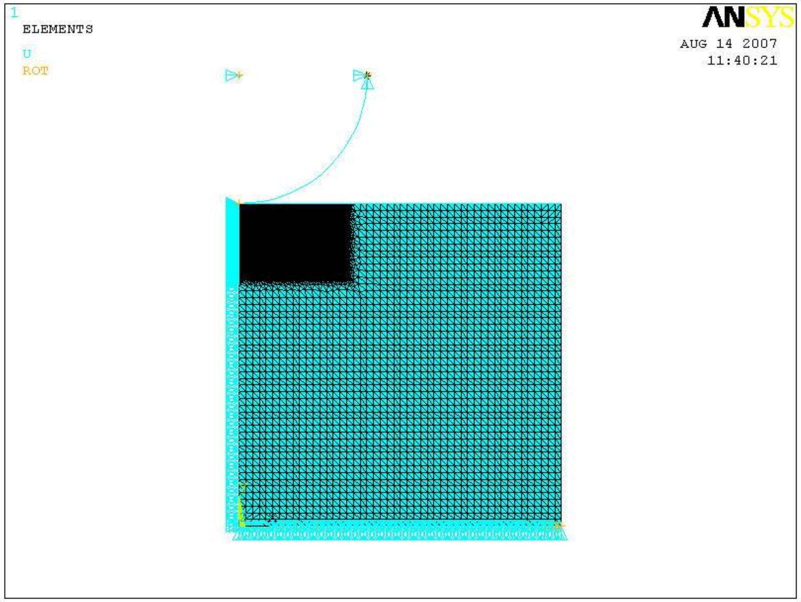
❖Ball Indentation tests were conducted using MTS 810 servo hydraulic test system

❖From the experimental setup, relative deformation (Interference) is measured using COD for the applied load

❖Circular Base plate is used to hold the flat specimens

- High Carbon Steel ball (r 2mm), Tungsten carbide ball (r 0.79mm) are used for indentation.
- The loading sequence is repeated in different positions of the flat specimens.
- The experiments were conducted under the normal laboratory conditions with the ambient room temperature, relative humidity and not environmentally controlled.
- The test specimens were ultrasonically cleaned with acetone before every experiment.
- Two ways can be employed in the MTS machine for conducting the experiments, either displacement control mode or force control mode.
- Normal load/interference can be applied in two ways, stepwise loading or continuous loading

Half Space indented by a Rigid Sphere



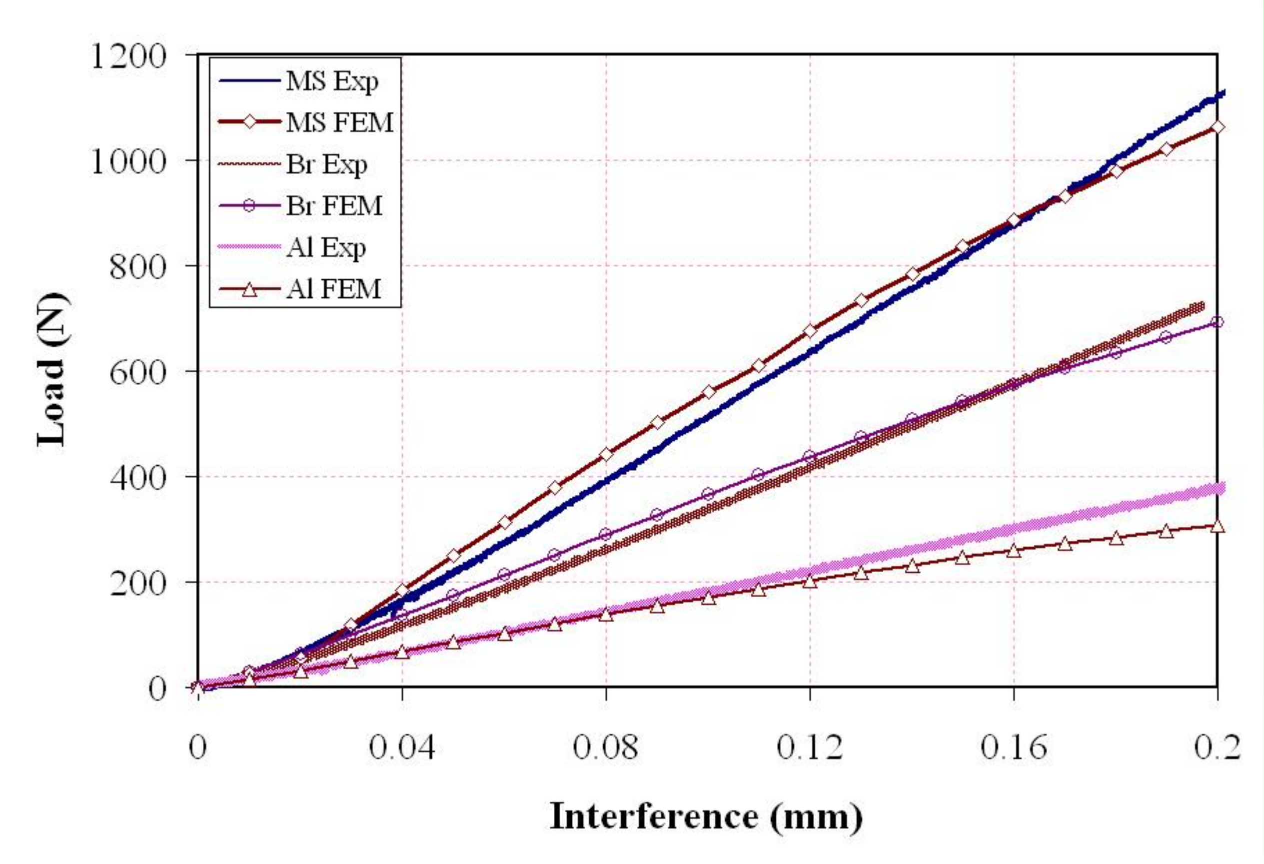
❖Material property is incorporated in ANSYS to calculate the exact contact parameters

❖Ball is modeled as a rigid and smooth flat is modeled for the base materials

❖Instead of bilinear option, multi-linear isotropic strain hardening option is used

❖Loading analysis is performed up to 0.2 mm deformation, from elastic to fully plastic state, FEM results are compared with experimental results.

Contact Load - Comparison

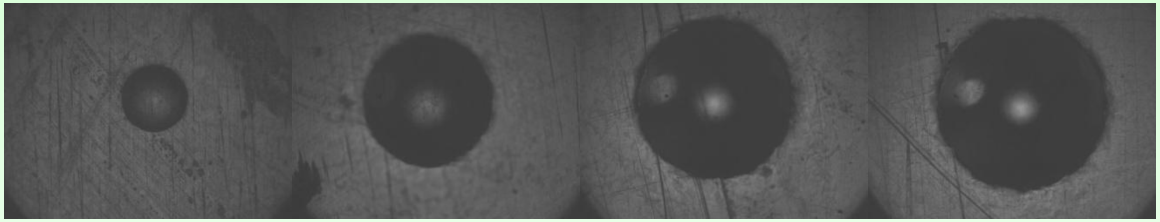


- From the experimental approach, the required contact load is recorded for the applied deformation
- Experimental contact load up to 0.2 mm deformation is compared with finite element half space indented by a rigid sphere contact results

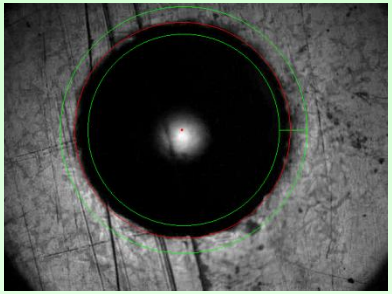
Contact Area - Comparison

Mild Steel Images for 0.05, 0.1, 0.15 and 0.2 mm Deformations

Brass Images for 0.05, 0.1, 0.15 and 0.2 mm Deformations

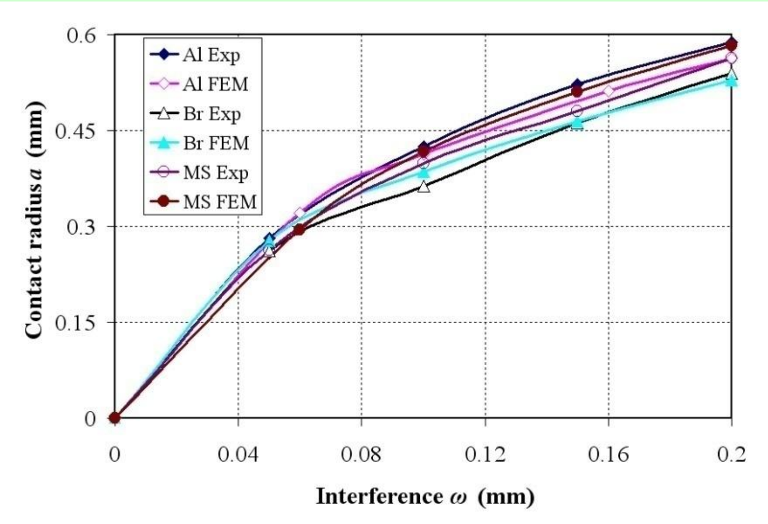


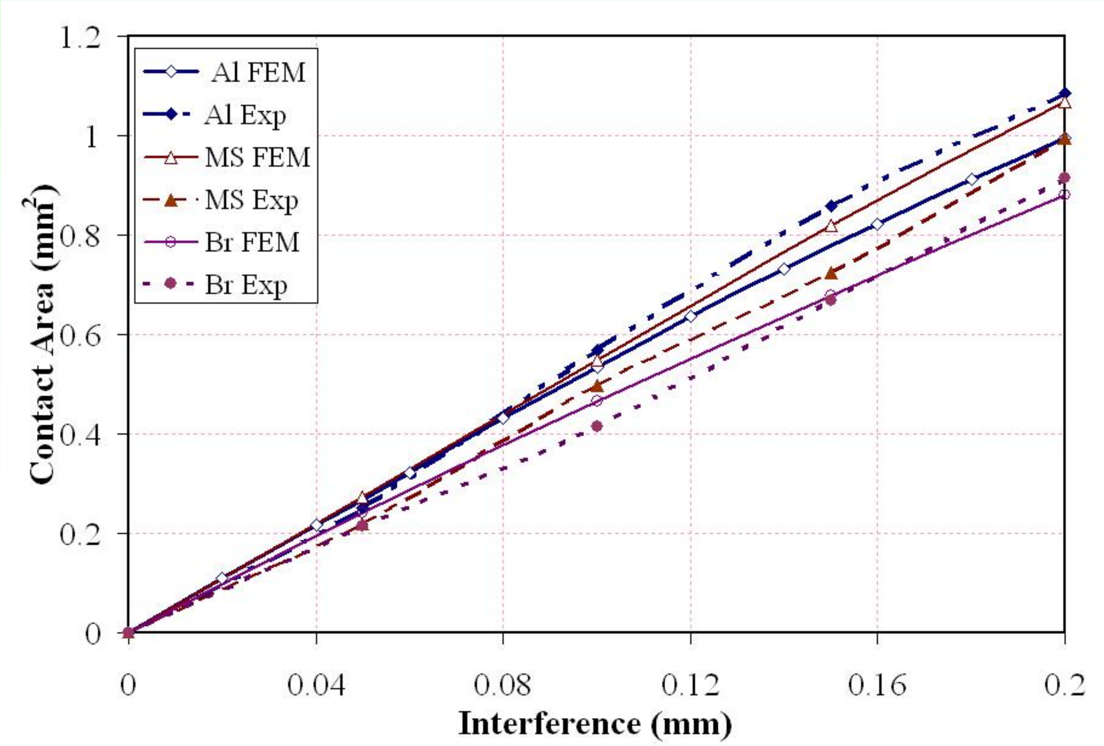
Aluminum Images for 0.05, 0.1, 0.15 and 0.2 mm Deformations



After the indentation process, the contact area was measured indirectly by using the residual plastic trace with a optical microscope.

Contact Area - Comparison





All the Best

Thank You and Please send your feed back

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