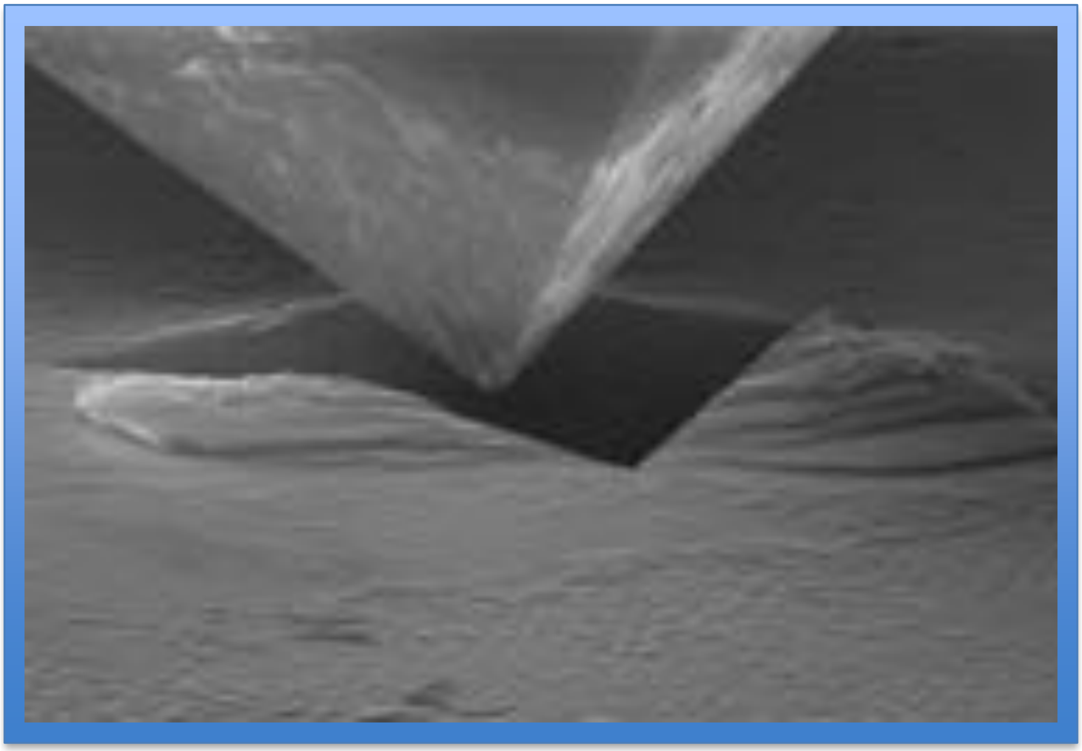

**ME 563: Nonlinear Finite Element Analysis**

# Nonlinear Finite Element Modeling of Nano-Indentation

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## Table of Contents

## Executive Summary

It is very difficult to measure mechanical properties on a very small scale, due to its increasing demand and more and more researches are conducted on very small scale, it become more and more important. Nano-Indentation test has been developed to be one of the most powerful tools to extract elastic modulus and hardness of the specimen material by obtaining load-displacement measurements. In this project, we conduct Nonlinear Finite Element Modeling of Nano-Indentation using FEM software ABAQUS. Some basic material properties and loading parameters will be taken from some reference papers about Nano-Indentation Tests. By conducting our finite element model, which is validated by comparing our results with the data from the reference paper. Due to possible influence that the friction coefficient of the material and substrate may have, we will also conduct some different models to study the influences.

## Acknowledgements

We would like to express our deepest appreciation to all those who provided me the possibility to complete this report. A special gratitude we give to Dr. Kraft, who brought us to explore the field of nonlinear simulations and helped us to compolish the project.

Furthermore we would also like to acknowledge with much appreciation to our classmates who helped us to do the projects and sharing brilliant ideas with us.

## Section 1: Background and Project Plan

One of the methods widely used for measuring mechanical properties of nanostructured materials, thin film and coating technologies is depth-sensing indentation at low load, often termed ”nanoindentation”.

A standard experiment set-up for nanindetation of thin films is schematically depicted in Figure 1(a). During the nanoindetation process, an indenter is pressed against the thin film, which is supported by a substrate.

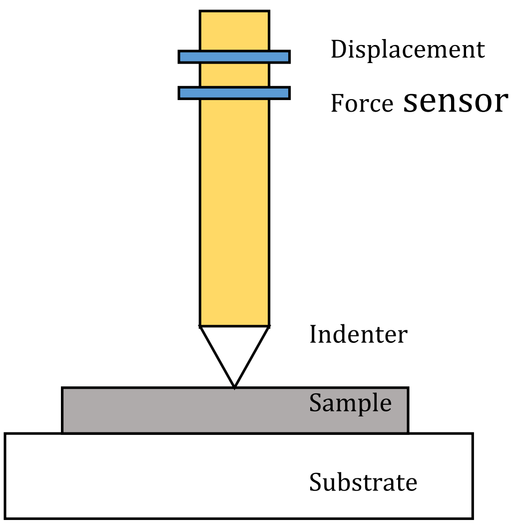


**Figure 1(a) Nano-indentation illustration**

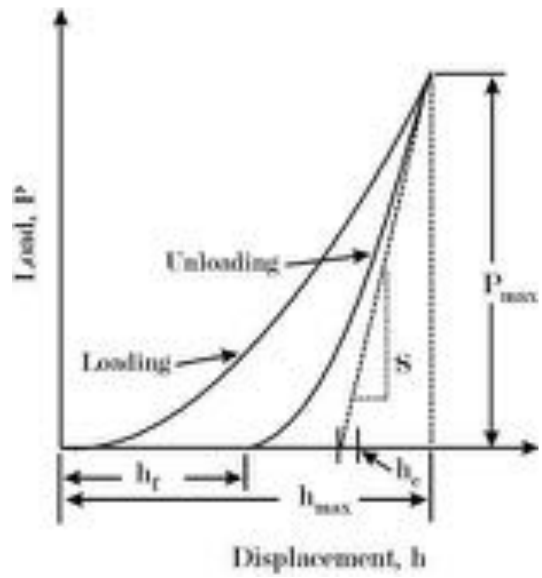


**Figure 1(b) Displacemen-Loading curve**

The advantage of nanoindentation testing is the test requires only small volume change so that it can be achieved at very small scale applying on thin film and study of nanostructure. Coupled with development in instrumentation, nanoindentation is now the universal tool for mechanical property characterization at small lengths and size scales. This technique has been employed not only for measuring the local mechanical properties, such as hardness and modulus of elasticity of materials, but for probing the early stages of deformation and transition from elasticity to plasticity. Indentation in metallic materials has been of particular interest due to complexity of crystalline deformation mechanisms in relation to the state of stress with geometrically different indenter tips and formation of pile-ups or sinking.

When a material is indented, it generally forms either pile-up or sink-in with respect to the indented crystal plane depending on various factors like strain hardening and the elastic modulus to yield strength ratio. Nanoindentation calculations use the standard Oliver and Pharr method to calculate the hardness and elastic modulus.

The load applied on the indenter and the indentation depth is recorded by two sensors above the indenter. As Shown in figure 1(b), the slope of the curve upon unloading is very important, because based on this slope the reduced Young's modulus of the thin film can be calculated. As the thin film is usually supported by a substrate during nanoindetation, the load-displacement curve may be affected by the mechanical properties of the substrate.

In this project, we will simulate the nanoindentation process of copper thin films and with different friction factor between the indenter and the copper film to study the effect of friction.

## Section 2: Development and Description of the CAD Geometry

In our project, the indenter we used was conical with radius of 100nm, the thin film in our model was made of copper, which is a thin cylinder with radius of 1000nm and height of 100nm, as shown in the below.

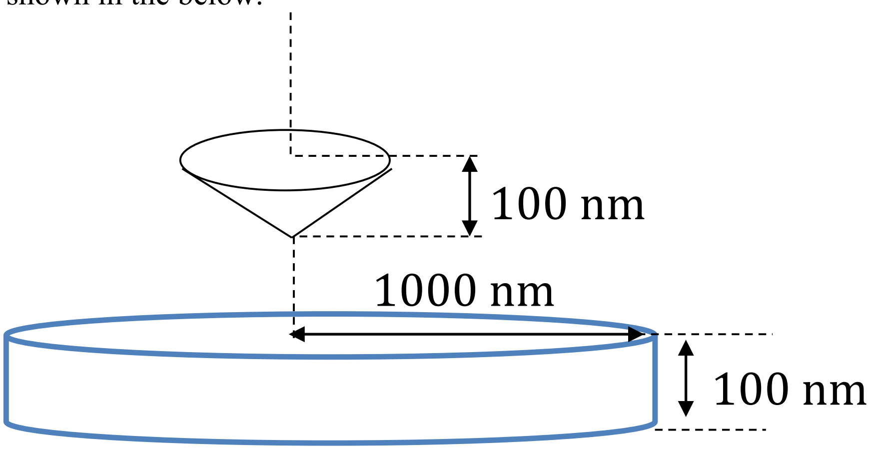


**Fig.2.** schematic of nano-indentation geometry model

In our geometry model, both indenter and thin film are axi-asymmetric, which provides a good symmetry in our model, thus we could simplify this 3D model into 2D model with symmetry.

## Section 3: Development of Finite Element Meshes

Due to its symmetry, we could simplify our model into 2D model by using its axiasymmetry, which is shown in Fig. 3.

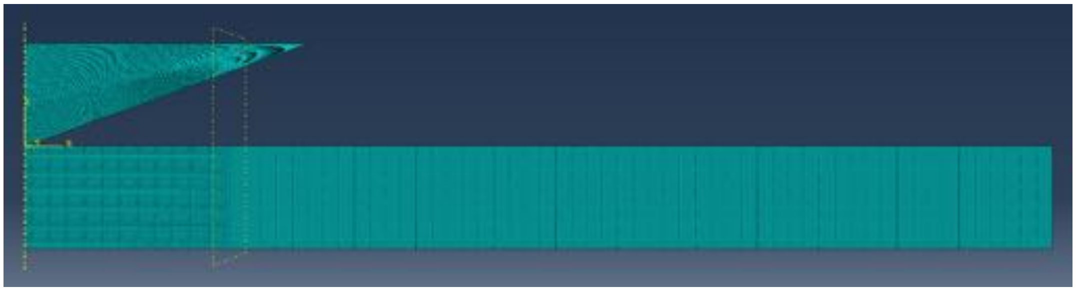

**Fig.3.** Finite Element Model of Nano-Indentation

From our finite element model, we can see that the mesh close to the contact area is much finer than the area that is far from the indenter, which on the hand could provide enough mesh for our calculation accuracy, on the other hand, the coarse mesh could prevent time consuming due to too fine mesh in the whole model, which could save a lot of time.

## Section 4: Development and Description of the Model Assembly and Boundary Conditions

In the simulation we assume that the substrate is large and heavy enough so tha we can neglected the infulunece of the substrate. For the boundary condition, we fixed the bottom of the copper and set a symmetric boundary condition in the middle due to the symmetry of the model.

## Section 5: Development and Description of Model Interactions

The indenter and copper film are two separated parts and a friction contact was set in the two contacting surfaces.

## Section 6: Analysis of Finite Element Model

Two steps were set up for the simulation. In step 1 the indenter is given a displacement boundary condition to move downwards 50nm and in step 2 the indenter move back to the initial position. The Nolgem was turned on. Since it was a 2D model so the simulation did not take too much time.

For the material, the indenter in our project is made from diamond, with young's modulus of 1147 Gpa and poisson's ratio of 0.3. In our model, the indenter is set as linear elastic material. The thin film is made of copper, which is elastic-plastic model, the constitutive behavior is shown below.

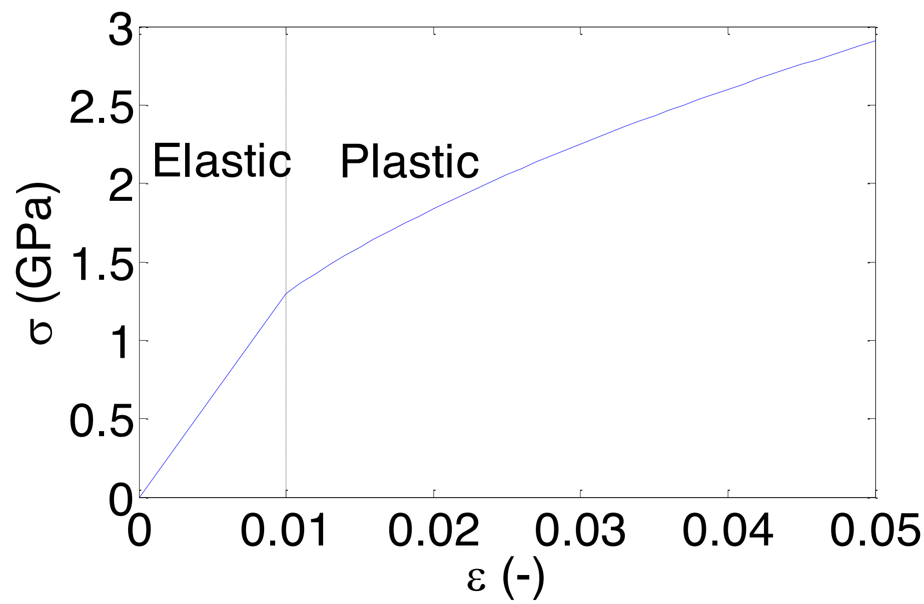


**Figure 4.** Constitutive behavior of copper

## Section 7: Summary of Major Findings

For nano-indentation of bulk materials, the reduced modulus of the studied material can be calculated analytically with the following equation:

$$E_r = \frac{1}{\left(\frac{1-v_s^2}{E_s}\right)+\left(\frac{1-v_i^2}{E_i}\right)}$$

in which $E_s$ and $v_s$ are the Young's modulus and poisson ratio of thin film to be studied in our model, and $E_i$ and $v_i$ are those for the indenter.
At the meantime, the reduced Young's modulus could also be measured experimentally with the following equation:

$$E_r = \left(\frac{\pi}{4}\right)^{1/2}\left(\frac{1}{A_c}\right)^{1/2}\left(\frac{dP}{dh}\right)_{unloading}$$

Where $A_c$ is the contacting area between the indenter and the film, and $(\frac{dP}{dh})_{unloading}$ is the slope of the load-displacement curve upon unloading.
A displacement load was applied on the top surface of the indenter, of which the maximum displacement is 30nm. Two steps including one step of displacement load and the other of unload were created in our model. The stress distribution is shown below.

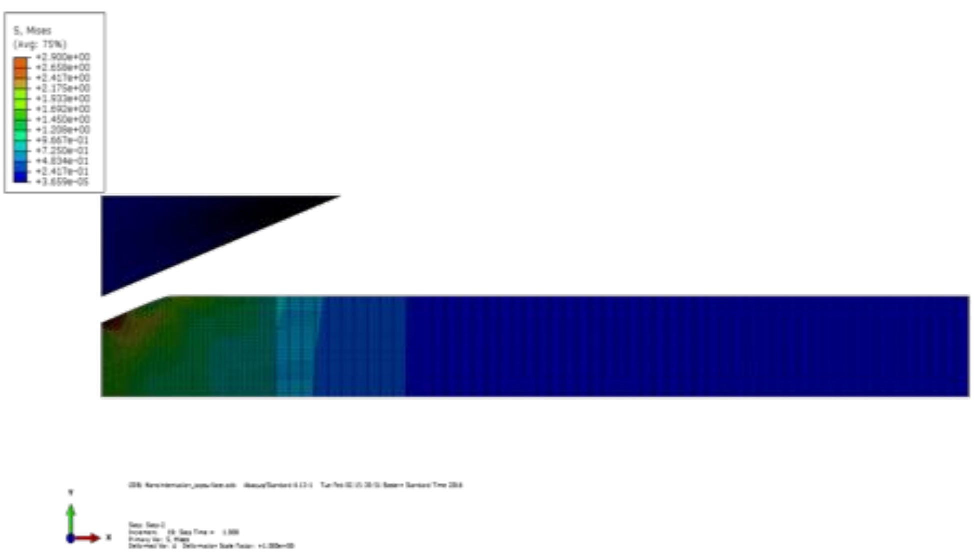


**Fig.5.** Stress distribution of nanoindentation model

The simulated result of load-displacement curve was shown below.

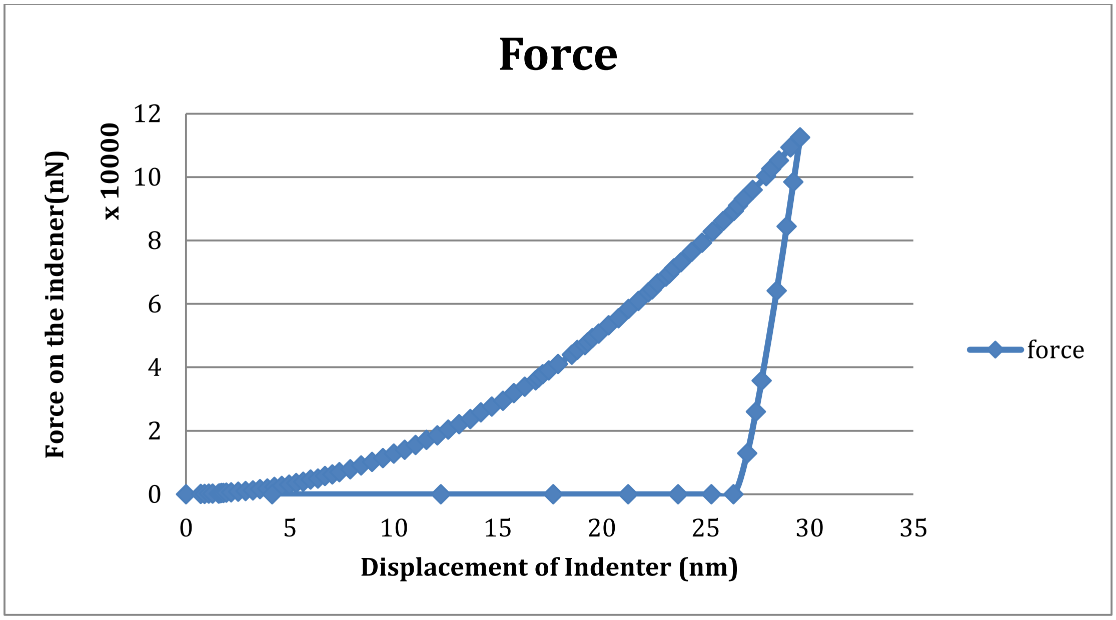


**Fig.6. load-displacement curve**

By applying the theoretical and experimental calculation of the reduced Young's Modulus, we could get the results shown below:

$$E_r = 119.38GPa, for\ theoretical\ result$$
$$E_r = 117.49GPa, for\ simulation\ result$$

By using theoretical result, we could get the unloading curve value, so we could compare the two slope in one figure, which is shown below:

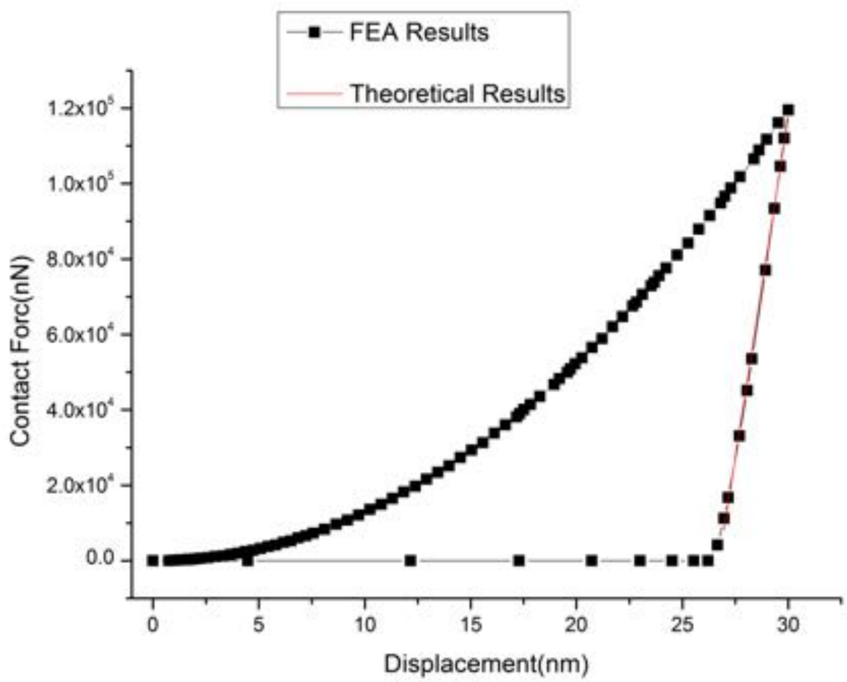


**Fig.7. FEA and Theoretical results comparison**

Thus, we could conclude that numerical simulation is a reliable method and could provide useful information for Nano-Indentation.

3. Study of influence of friction coefficient

Friction coefficient is an important factor that could influence nano-indentation results. In order to study the influence of friction coefficient on the nano-indentation, four sets of numerical simulations were applied to study. Table 1 shows the four different numerical simulation sets.

| Test Number | Contact Type | Friction Coefficient |
|---|---|---|
| 01 | Frictionless | 0 |
| 02 | Friction | 0.01 |
| 03 | Friction | 0.015 |
| 04 | Friction | 0.03 |

Tab.1. Different friction coefficients in numerical simulations

After setting different values of friction coefficient, with all the other parameters being kept the same, and we could get the results. We are mostly interested in the stress distribution when the nano-indentation get the deepest indentation and after the test. Below shows the stress distribution when nano-indentation get the deepest location.

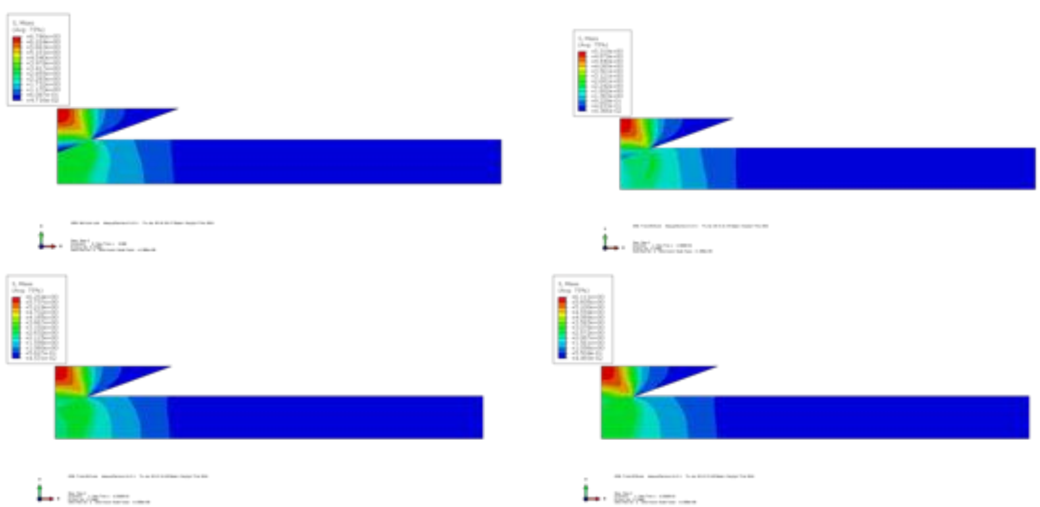

Fig.8. Stress distribution at deepest indentation

The peak stress is also compared, which is shown in table 2.

| Friction Coeff | 0 | 0.1 | 0.15 | 0.3 |
|---|---|---|---|---|

| | | | | |
|---|---|---|---|---|
| Peak Stress(Gpa) | 7.768 | 5.31 | 6.254 | 6.11 |

Tab.2. Peak stress when nano-indentation at 30nm location

Also, the stress distribution after unloading is also studied, which is shown in Fig.9.

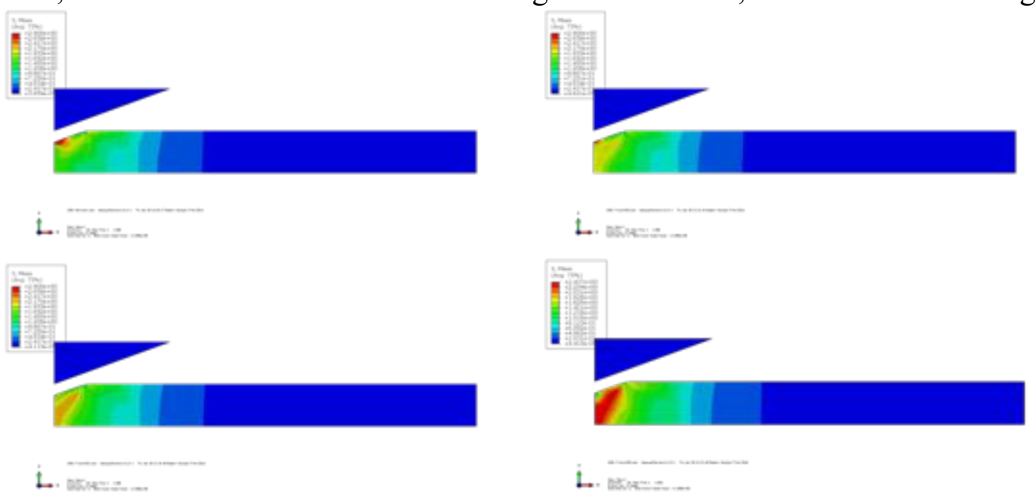

Fig.9. Stress distribution after unloading

And the peak stress is also compared in table 3.

| **Friction Coeff** | **0** | **0.1** | **0.15** | **0.3** |
|---|---|---|---|---|
| Peak Stress(Gpa) | 2.90 | 2.90 | 2.90 | 2.437 |

Tab.3. Peak stress comparison after unloading

Finally, the load-displacement curve is compared in one same figure, which is shown in Fig. 10. From the stress distribution figure shown above, we could see that the stress distribution with friction has much difference with the one without friction, and the peak stress would have a tendency of going down with friction.

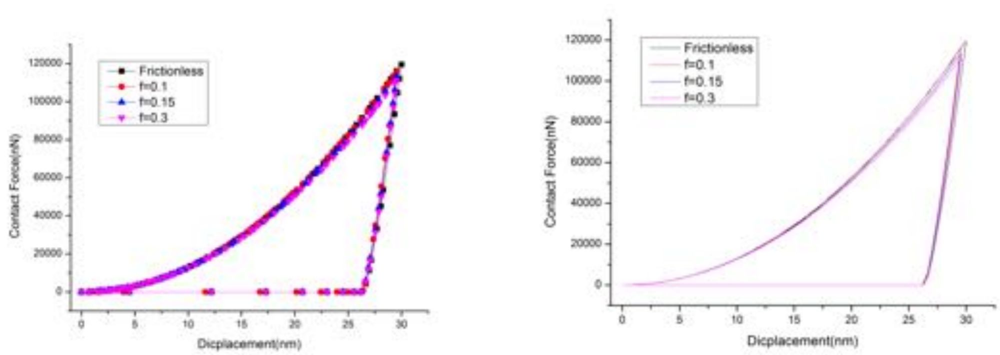


Fig.10. Load-displacement curve with four different friction coefficient

And the peak load is isolated from the data, shown in Table 4.

| **Friction Coeff** | **0** | **0.1** | **0.15** | **0.3** |
| --- | --- | --- | --- | --- |
| Peak contact force(nN) | 119531 | 115706 | 113421 | 111317 |

From the peak contact force table, we could conclude that the peak contact force would decrease as the friction coefficient goes down, with other conditions being the same.

**Conclusions**:

Nano-Indentation is very important for those tests at very small scale, by conducting our project, we could get following conclusions:
1. Numerical simulation is a reliable method that is used to predict material properties in real life.
2. Friction has influence on stress distribution during the numerical simulation, as well as the residual stress after test.
3. The bigger the friction coefficient, the smaller peak contact force would be got from the test

## Section 8: Works Cited

[1] X. Huang et al, Journal of Composite Materials, v40, p1393 (2006)

[2] J. Knapp et al, Journal of Applied Physics, v85, p1460 (1999)