Predicting nanoindentation behaviour of Ni-P coatings using finite element analysis

Abhishek Arora*, K Uday Venkat Kiran, Ravikumar Dumpala

Department of Mechanical Engineering, Visvesvaraya National Institute of Technology, Nagpur 440010, India

*Corresponding author: abhishekarora@students.vnit.ac.in

Abstract. Electroless nickel coating is an autocatalytic reduction of metallic ions from an aqueous solution containing a reducing agent. Electroless nickel coatings (Ni-P) are very popular because of their unique characteristics such as excellent corrosion resistance, chemical inertness and high hardness. Aim of this paper is to simulate Indentation process on Electroless Nickel coated steel specimen by finite element method. A two-dimensional (2D) asymmetric model is modelled/meshed and analysed using ANSYS. The simulation yields a loading- unloading curve similar to the curve that is generated using the actual Indentation experiment. The curve is useful tool to determine the mechanical behaviour of the coating. The various Material Properties required for the simulation is taken from the references.

1. Introduction

To improve the lifetime of the components in tribological applications there is huge demand for protective hard coatings. Auto catalytically deposited Electroless Nickel phosphorus coatings has excellent mechanical (hardness and elastic modulus) and tribological properties (wear and coefficient of friction) [1]. Nanoindentation is a widely used non-destructive technique (NDT) technique that is used to study the various mechanical properties, such as hardness, poissons ratio and elastic modulus, on small scales or near surfaces. Nanoindentation method rely on load and depth sensing to measure properties like Elastic modulus and hardness. In this test the indentation depth is in the order of nanometer and the residual indentation diameter is often in the order of nanometer [2]. Contrary to destructive testing methods like tensile testing, this method has negligible damage to the surface of the sample used. To extract mechanical and tribological properties in thin coatings with thickness in few microns Nanoindentation technique can be successfully employed. Very few researchers employed Nanoindentation technique to extract mechanical properties (hardness and elastic modulus) of Electroless Ni-P coatings.

Finite element method (FEM) can be employed to characterize mechanical properties of hard thin film coatings by simulating Nanoindentation process. Some investigators have studied the indentation process using the numerical approach of finite element method. Simulating the Nano indentation process is highly complicated owing to the nonlinear behaviour of the process [3]. M. Lichinchi et al. (1998) showed that the 2D axisymmetric model gives same result as a 3D model would give if the conical indenter has area function same as of the Berkovich tip. M. Sribalaji et al [4] has carried out the Nanoindentation test on an Electroless Nickel coated steel 4140 specimen, during his work he has used a
diamond indenter with tip curvature of 100 nm. The test was carried out with a loading rate of 20 µN/sec with a max loading of 1000 µN Which was applied for 4 sec as the holding load and then unloaded completely. The maximum indentation depth achieved during the Nano indentation process was 50 nm and the permanent plastic deformation undergone by the coated specimen was 25 nm. The parameters required for the finite element simulation has been extracted from his work. The aim of this paper is to simulate the nanoindentation process on electroless nickel coated 4140 steel specimen using two-dimensional (2D) axisymmetric model. The experimental and finite element results are then compared with each other.

2. FE modelling
The finite element modelling of the Nano indentation is highly complex owing to the nonlinear nature of the problem. Hence 2D axisymmetric model was solved using ANSYS V16.2. The various properties used in the FE analysis is given in the ‘Table 1’. FE model used in the analysis is shown in the ‘Figure 1’.

Table 1. Various material properties used in the finite element modelling of the Nanoindentation of electroless coated steel specimen

| COMPONENT | MATERIAL | PROPERTIES |
|-----------|----------|------------|
| 1         | Substrate | Steel 4140 | Elastic modulus: 200 (GPa)  
Poisson’s ratio: 0.3   |
| 2         | Coating  | Electroless Nickel as-deposited | Elastic modulus:146±5.1 (GPa)  
Poisson’s ratio: 0.3  
Initial Yield stress: 11.8 (GPa) |
| 3         | Indenter | Diamond | Elastic modulus:1140 (GPa)  
Poisson’s ratio:0.07 |

Following assumptions are considered for the simulation to proceed.

a) The material is considered as completely homogeneous, isotropic and defect free.
b) The residual stresses in the coating is assumed to be negligible.
c) During the simulation the material undergoes the elastic perfectly plastic deformation.
d) The contact between coating and substrate is considered as perfectly bonded so that there is no delamination during the indentation process and the contact between coating and the indenter is considered as frictionless.

A two dimensional axisymmetric finite element model was modelled in ANSYS V16.2 into three parts a substrate, a coating and an indenter as shown in ‘Figure 1’. To extract results using the exact geometry used during the test is very difficult, therefore the geometry was scaled suitably to maintain the accuracy of the analysis. The Berkovich Indenter which is originally pyramid shaped is highly complex to model, hence a conical indenter with tip of semi-angle 70.3° such that the total surface area of the indenter remains same was modelled to simplify the geometry [2]. Asymmetric contact analysis was considered during the analysis to save computation time. The indenter was considered as the target surface and coating as the contact surface. The model was fine meshed with the quadrilateral elements of size 0.01 as shown in ‘Figure 2’. The number of elements are 16063 and number of nodes are 49116. The indentation depth should be large enough for the result to be unaffected by the surface effect neither should be so large that substantial substrate effect is observed, in general 10 percent rule is followed for the Nanoindentation process such that substrate effect is less than 2 percent. Following boundary conditions are imposed during the simulation process.
a) The base of the substrate is fixed.
b) The displacement boundary condition is imposed on the indenter and the corresponding reaction force is acquired at the fixed support.
c) Axisymmetric boundary condition is imposed on the two-dimensional (2D) model such that result corresponding to the actual three dimensional (3D) model can be evaluated.

Figure 1. Geometry of the FE model

Figure 2. Meshing pattern of the FE model

3. Results & Discussion

The Finite element model of the Nano indentation of the electroless nickel coated 4140 steel was successfully solved. ‘Figure 3a’. Shows the max elastic plastic deformation of the specimen at the end of loading step. 'Figure 3b' shows the residual plastic deformation of the specimen at the end of the unloading step. 'Figure 4' shows the load displacement curve generated by the simulation of the Nano indentation process on the electroless nickel coating with the conical indenter. During the process 60 % elastic deformation and 40% plastic deformation is obtained for a total deformation of 50 nm. The experimental results are 50 % elastic deformation and 50 % plastic deformation [4]. The reaction force obtained for 50 nm indentation depth is 792.4 µN, the experimental maximum load applied was 1000 µN [4].
Figure 3. Deformation for 2d axis-symmetric FE model a) at the end of loading step b) at the end of unloading step

![Image of load displacement curve](image.jpg)

Figure 4. Load displacement curve

4. Conclusions
In the present work the finite element modelling and analysis of the Nano indentation process of electroless nickel coated 4140 steel was attempted. A successfully converged solution was obtained but the analysis fails to achieve the exact loading curve obtained during the experiment, and further study is required to address the issue.

5. References

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