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Measurement of mechanical properties of nickel thin film over steel substrate through simulation of Nano Indentation Technique

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Abstract: Nickel is an important element used in many industrial applications. It can be used as alloying element as well as in many coating applications. Thin film of nickel coatings play an important role to protect surface of metals and also prevent from degradation and friction of metallic surfaces. Protective coatings based on nickel thin films not only protect from environmental effects but also can enhance the mechanical properties of coated surfaces applied to any metallic surface. In this research work nickel based thin film are coated on steel substrate to enhanced electrical, mechanical, magnetic and chemical properties. Finite element simulation of Nano indentation technique is an appropriate method to characterize mechanical properties of thin films. In this present work, a thin layer of nickel on steel substrate has been analyzed by finite element modeling of Nano indentation technique. Various mechanical properties like hardness, elastic strength, shear and normal stresses can be measured but in this research work most important properties are studied. It was found that nickel based thin film coating has adverse effect on steel surface and as a result mechanical properties have been improved that can be verified from simulation of Nano indentation results.

Keywords: Thin Film, Coating, Nickel, Steel Substrate, Simulation, Finite Element Modeling.

1. INTRODUCTION

Nickel is a special element found on earth's crust and it can be used in various fundamental applications in materials science and metallurgy. Nickel can be used as alloying agent as well as it can be applied as a coating material over many metallic surfaces.

Mechanical properties of nickel thin films over steel substrate are a subject of interest. But unfortunately there is a less work done so far on this area. In this research work mechanical properties of nickel thin films upon steel substrate has been measured using Nano indentation by applying finite elemental analysis simulation. Thin film coatings nowadays getting attention towards the materials scientists because of their good quality, ease of fabrication and applications to many industrial work and excellent mechanical properties (Alaboodi, and Hussain, 2019). (Abro. and Moria 2020), (Abro. *et al.*, 2019). (Abro. *et al.*, 2018) (Abro., *et al.*, 2019) They are very helpful from wear resistance along with friction effects. The best possible method for measuring the thickness of these thin films is by Nano indentation process because Nano indentation provides an accurate method of analyzing data obtained through this destructive method. Variety of mechanical properties can be measured and analyzed through Nano indentation (Abro, *et al.*, 2018). (Abro, *et al.*, 2020) (Abro, 2018) (Chandio, *et al.*, 2019).

Nano indentation technique can be employed to strain rate sensitivity, internal friction, and damping. Nano-indentation is anon-destructive NDT technique that uses Nano sized indents less than 200 nm (based in ISO 14577-1, hence called Nano indentation). Measuring mechanical properties of materials by conventional mechanical test methods require destruction and large size of materials which may not be convenient in some cases. An alternate approach is to employ Nano-indentation technique to measure mechanical properties of bulk materials and thin coatings (Abro, *et al.*, 2019) (Abro, *et al.*, 2019) (Mehdi, *et al.*, 2019) (Chandio, *et al.*, 2018). (Lizeng Ling 2010).

2. MATERIAL AND METHODS

Experimental Procedure

2.1 Finite Element Modeling

Indentations were simulated using commercial FEA software (ANSYS WB 16). Two-dimensional axial symmetric models were defined to reduce computational time without loss of accuracy **(Fig. 1).** Three different types of indenter, Berkovich with half cone angle 70.3, spherical indenter of radius 50 µm and cylindrical indenter of radius 50 µm were used. The dimensions of specimens were so large that any further increase in dimension would not affect the results.

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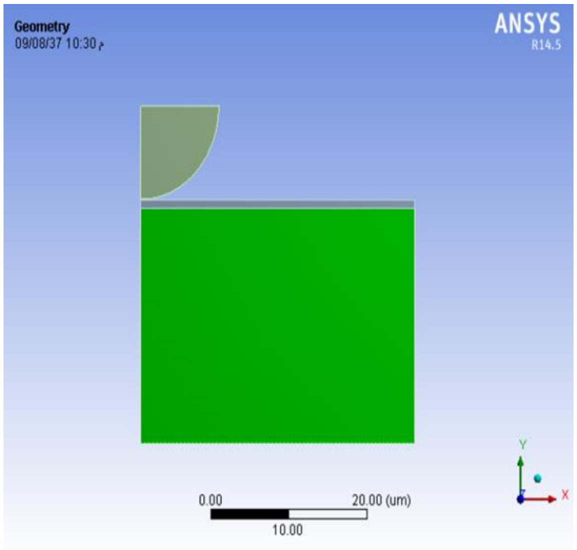

Fig. 1: Nano indentation procedure

2.2 General Setting

The general settings that were made are given below.

i) Coating and substrate materials were assumed to exhibit plastic behavior with bilinear isotopic hardening. The indenters have been assumed very hard and rigid material and represent elastic behavior. The mechanical properties of indenter, thin layer and substrate are given below in **(Table 1).**

Table 1 Mechanical Properties of steel sustrate.

Item	Young's Modulus (GPa)	Poison's ratio	Yield Strength (MPa)	Tangent Modulus (GPa)
Coating	229	0.3	500	100
Substrate	200	0.3	250	100
Indenter	1140	0.06	-	-

ii) Each indenter has been discretized in to elements of size 0.1 µm, substrate into elements of size 0.05 and thin coating of elements of size 0.001.

iii) Thin layer was assumed to be bonded with substrate in the contact whereas contact between indenter and layer was assumed to be frictionless.

iv) To simulate indentation, indenter has been given downward and then upward displacement upto 0.3 µm in series of 11 steps graph of which is shown in figure. Inward displacement represents loading the loading and upward displacement is equivalent to unloading.

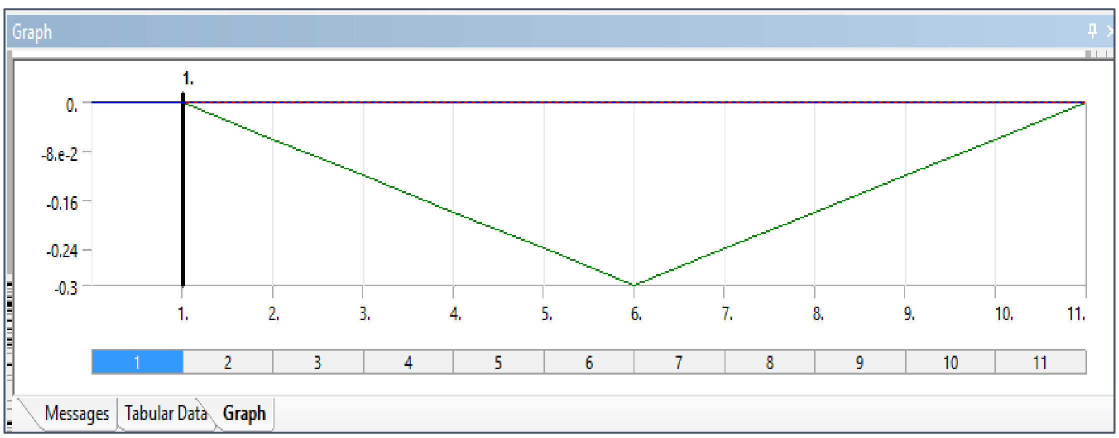

Fig. 2 Simulation of Indenter Movement

Lower portion of the substrate was fixed whereas nodes on central axis of axisymmetric problem were assumed to be moveable along y-axis only as shown in **(Fig. 3).**

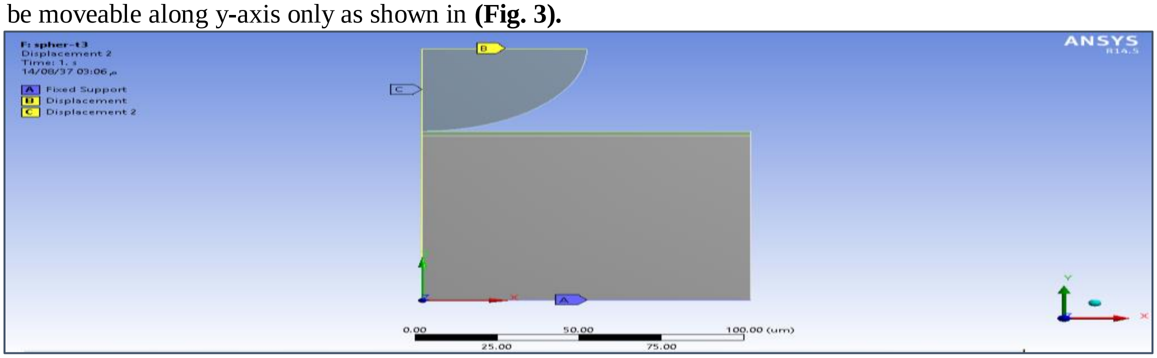

Fig. 3 Loading and Boundary conditions

v) Load-displacement graph, von-mises stresses, maximum and minimum principal stress, normal stress and maximum shear stresses in layer as well in substrates were analyzed.

3. RESULTS AND DISCUSSION

a) Mechanical Properties

i. Hardness

Load displacement graph has been obtained as shown in **(Fig. 4)**.. Using Olive and Pharr method, hardness can be determined.

Stiffness S is

$$S = \left(\frac{dp}{dh}\right) \text{ at hmax = Slope}$$

So $S = (18000 - 10000)/ (0.25\text{-}0.20) = 16000\ N/\mu m$

Contact depth is given by

$$h_c = h_{max} - \frac{\varepsilon P_{max}}{S} = 0.29 - \frac{1x27000}{160000}$$

$h_c = 0.12\ \mu m$ ---------------------- (1)

Contact area for spherical indenter can be calculated by following equation.

$$A = 2 \times \pi \times R \times h_c$$

$$A = 2x\ 3.14x\ 50\ x\ 0.12$$

So $A = 37.7\ \mu m^2$

$H = \frac{\text{Max Load}}{\text{Area}} = \frac{27000}{37.7} = 716\ MN/mm^2$------------------------------ (2)

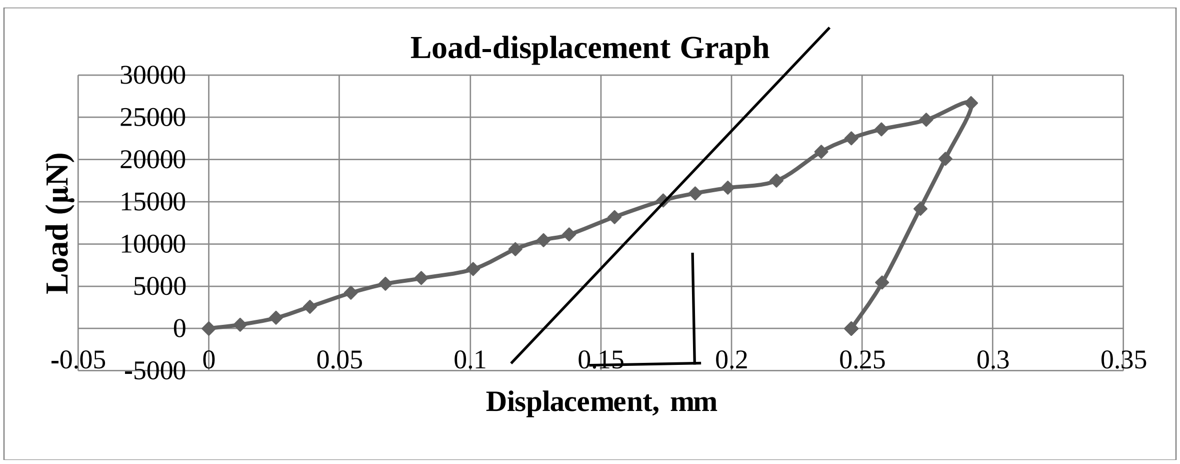

Fig. 4 Load displacement graph.

ii. **Strain Energy**

Stress-strain curve for elastic region has been shown in **(Fig. 5)**.. Elastic strain energy can be found by calculating area under this graph. Also stress-distribution plot and strain-distribution plot are obtained to show variation of stresses and strain fields as the indenter traverses in the film.

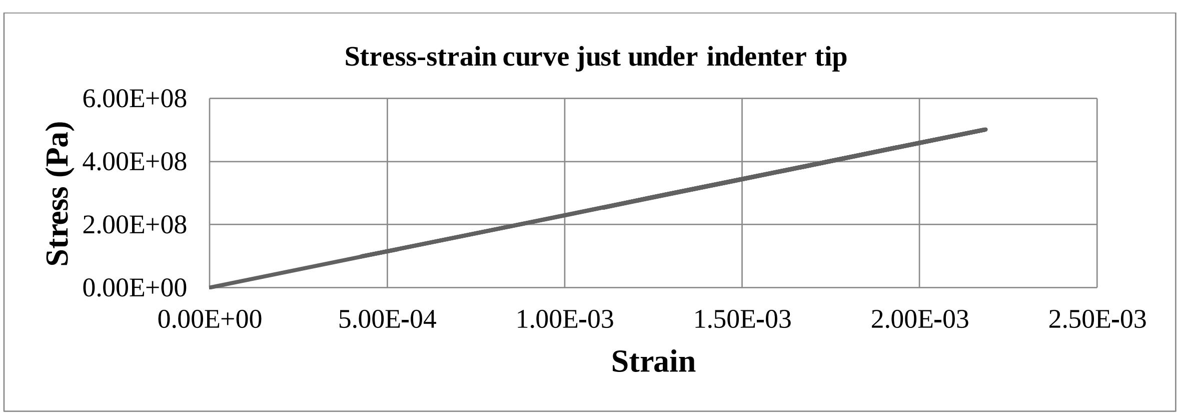

Fig. 5 Stress-strain curves.

$$\text{Strain Energy} = \frac{1}{2} * 2.2\text{x}10^{-3}\text{x}\ 5\text{x}10^{8}\ = 550\ \text{KJ}\text{-------}(3)$$

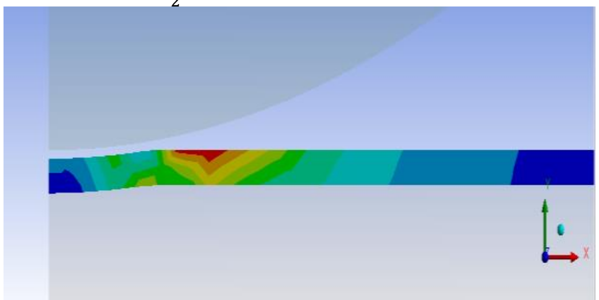

Fig. 6 a)Von-mises stress distribution in nickel film

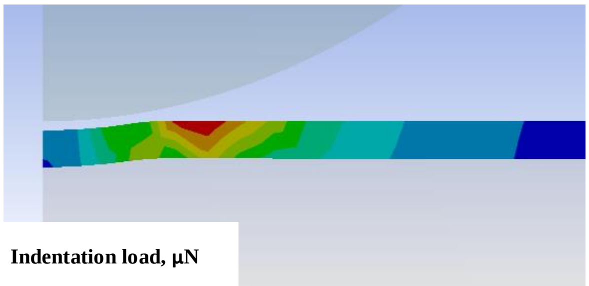

Fig. 6 b) Strain distributions

iii. **Maximum Principal and maximum normal Stress**

Maximum principal stress and tensile stresses impart tensile strength of nickel layer. Stress distribution plot of last step has shown in **)** and **(Fig. 6** a.**b)**. **(Fig 7 a.b)** Maximum principal stress was found to be 419 MPa and maximum tensile strength was 73 MPa

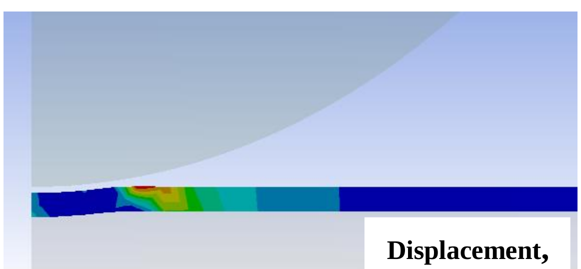

Fig. 7 a) Maximum Principal Stress

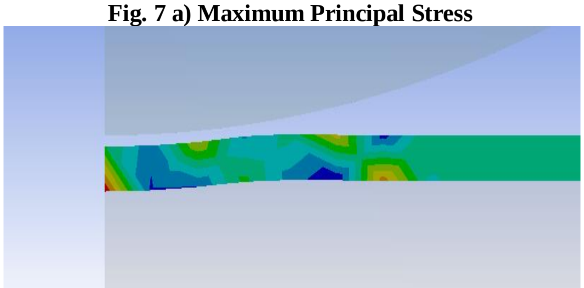

Fig. 7 b) Maximum Principal Stress

iv. **Maximum Shear Stress**

Maximum shear stress determines the wear strength of the films. In this case it was found to be 305 MPa as shown in **(Fig. 8).**

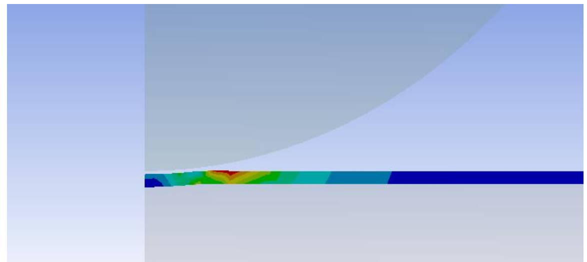

Fig. 8. maximum shear stress

b) Validation of results

In order to validate our work, we have taken a published paper. In this paper, Nano indentation technique been simulated as an axis-symmetric two-dimensional contact problem in ABAQUS software to investigate the effect of mechanical properties. Spherical indenter of radius 10 µm was used on layer of thickness of 1 µm. We simulated the same problem on ANSYS Workbench with same approach that was used for analysis and results were comparable as shown in **)** and **(Fig. 8)**..

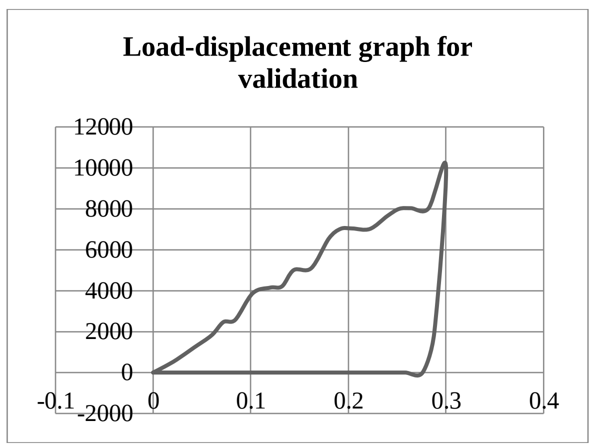

Fig. 9 Load displacement graph for validation

Maximum load against maximum penetration is 11000 µN (11 mN) which is comparable with 13 mN given on the published paper.

4. <u>CONCLUSION</u>

To measure the mechanical properties of nickel based thin film coating over steel substrate a finite element simulation of Nano indentation technique is applied it is conclude that FEM is an appropriate method to characterize mechanical properties of thin films. Nickel film of 1 micrometer has been characterized and following results have been obtained Hardness= 716 MN/mm^2, Load-Displacement graph **(as shown in Fig. 9),** Stress-strain curve **(as shown in (Fig. 5),** Elastic strain energy (550 KJ), Maximum principal stress to find tensile behavior (419 MPa and 73 MPa), Maximum shear stress to find wear behavior (716 MPa).

4.1 RECOMMENDATIONS

- One can follow these lines to study the effects of variation of thickness on the already found properties.
- Influence of friction between indenter and film can also be investigated
- Multi-layer coatings and coatings of graded modulus can be characterized.
- Coatings of different material properties can be investigated.

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