Three Dimensional FE Modeling of Vicker Indentation Process for Black NiAl Coated Aluminum Substrate

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Abstract— **Black painted Solar collectors are main component of solar water heater system. This solar coating has high solar absorptance but high emittance. Moreover after some period, this low quality coating is getting separated from collector surface either because of corrosion or erosion. The solar selective coating of Black NiAl can be used to replace black paint because it has high solar absorptance and low emittance properties, less cost. To find whether this coating is reliable in high temperature condition one must have to find out its mechanical properties like hardness, young's modulus, etc. Current research is focused on to measure mechanical properties of black NiAl coated aluminum substrate and compare it with black painted aluminum. Recently, Microindentation process is widely used to measure mechanical properties of small volume materials. So, in this study microindentation experiment was performed on THV-Micro Vicker hardness tester using Vickers diamond square pyramid indenter to measure and compare mechanical properties of Black painted aluminum and Black NiAl coated aluminum. Hardness of Black NiAl coated is higher than Black Painted aluminum. Thus, Black NiAl coated aluminum has higher strength and wear resistance property. Three-dimensional (3D) axisymmetric model was modeled in CREO PARAMATRIC 3.0 modeling software and simulation was carried out in ANSYS 14.5 software and simulation was carried out to find total deformation at indenter and surface contact when load applied. Load-displacement plot obtained from FE simulation gives young's modulus value which is in good agreement with experimentally obtained young's modulus.**

Index Terms — Indentation, Micro-hardness, Young's modulus, Micro-indentation, Vickers indenter

I. Introduction

Surface coatings are one of the cost effective approaches against surface failure. In the last a few decades, development of protective coatings has become an active area in the field of materials engineering. A novel and affordable solar selective coating which exhibited higher solar absorption efficiency compared to the commercial black paint coating is used in most ordinary solar water heating systems (SWHSs) [1]. NiAl alloy coatings embedded into a black paint have excellent surface properties. Also, in cost\benefit analysis it shows that for a very small percent increase (around 1%) in the cost of the system, a gain of an average of 5°C (around 10%) is fairly acceptable especially with larger installations [1]. This coating must be durable in high temperature conditions. This can be finding out measuring mechanical properties like hardness and young's modulus of this new coated substrate.

To characterize mechanical properties of material, an Indentation process is used because it is simple and widely applied method. Conventional indentation methods use large loads and depth. Hence it is not suitable for thin surfaces. Micro-indentation, an indentation test in which the length scale of the penetration is measured in micrometers has been established as a basic tool for investigating mechanical properties like hardness, young's modulus of small volumes of material. Usually, indentation tips used in indentation process have a conical, pyramidal, spherical, cylindrical or wedge shape. In microindentation process pyramidal indenters (knoop, micro-vicker) are used.

In present study, microindentation process using Vicker pyramidal indenter made up of diamond material is used to measure mechanical properties of specimen. Vickers indentation process was simulated using the FE model developed in ANSYS 14.5 simulation software. Finite element simulation was carried out to investigate elastic /plastic deformation of Black NiAl coated Aluminum substrate under gradually increasing loading conditions. In the present study, a 3Dimensional axisymmetric model case was performed to simulate the elastic/plastic indentation process. The indenter used here is Vicker diamond pyramidal indenter have been employed simultaneously in the current finite element simulation based on a nonlinear contact model. Because of geometrical symmetry the considered domain can be reduced and only one fourth of the whole domain. Mechanical properties of material can be found out from load-displacement plot obtained after numerical simulation. This load- displacement graph obtained in numerical simulation is verified with microindentation experiment.

Here, Experiment was carried out on THV-Micro Vicker hardness tester. To measure the hardness of coated substrate microhardness tester is used of loading capacity (0.1-10N) and the Vickers indenter with the shape of a four-sided diamond pyramid with a square base and an apex angle between opposite edges of 136°. low loads are applied on the specimen and indentation diagonal is measured to calculate Vickers hardness of specimen. Young's modulus of coated substrate found out from experimental load – displacement graph.

II. Literature Review

A) Coatings used in solar collector Receivers

Ewa Wackelgard [2], in present paper study was carried out on Black nickel coating which was electroplated in a nickel- and sodium chlorine aqueous solution. This can be used in solar collector receiver system to increase

absorptance and lower a thermal emittance. However, this coating is not chemically or physically stable when working above 200° temperature condition.

M.R. Bayati [3], presented that Black Chromium coating can be used in solar collector system because it has high durability and good optical properties. It has slightly low absorptance than black nickel but it is stable up to 300°c temperature. While, electro deposition of black chrome on collector pipes require higher density current and use of toxic hexavalent chromium are major drawbacks.

Ehab Alshamaileh [1], showed the coating fabricated by embedding the NiAl alloy in black paint shows better performance compared to the untreated black paint by an average of 5°C over a period of 1 year with a small increase in cost of system. It must require measuring its strength and wearing resistance property to use it in high temperature conditions.

B) Methods used to find mechanical properties of small specimens or thin coated substrates.

Tadeusz Niezgoda[5], presented simulation of microindentation process using Vickers indenter on alumina ceramics. Elastic theory was applied. Numerical simulation of indentation process was based on elastic theory of material deformation to provide residual equivalent stresses during and after the indentation test.

A. Iost, D. Najjar, R. Hellouin [6], presented measurement of hardness of paint coating deposited on galvanized steels used for domestic appliances using microindentation process. Sacrificial zinc layer and the organic barrier layer were used to protect steel. Strong plastic deformation of the film was considered while measuring Mechanical properties under the applied load.

Pravin S. Pandurea, VijayKumar S. Jatti [7], in this paper modeling and simulation of nanoindentation process carried out on DLC coated high speed steel (HSS) by finite element method. A spherical diamond indenter was used in simulation process of indentation.

L. Wang [8], described micro-indentation simulation process on yttria stabilized zirconia thermal barrier coatings (TBCs) with microstructural characteristic of columnar grains and sub-grains. It was performed by finite element method (FEM) based on a nonlinear contact model. Comparison of influence of the indenter shape (spherical indenter and flat indenter) on the elastic/plastic response behavior of the TBCs with microstructural characteristic of columnar grains and sub-grains was shown in detail.

Yuan Zhanwei, Li Fuguo [9], mechanical properties i.e. microhardness and Young's modulus of SiC particles reinforced aluminum matrix composites were measured with microcompression-tester (MCT) and analysis of the elastic–plastic properties of matrix was carried out in ABAQUS simulation software. Suggested, variations in microhardness and young's modulus are highly dependent on loading conditions.

Aim of present work is to simulate the microindentation process on black NiAl coated aluminum substrate. Present study includes experimental microindentation process on Black NiAl coated aluminum sample and three dimensional (3D) axisymmetric modeling of the system in Ansys 14.5 FE simulation software. The indenter used was Vicker indenter of diamond material and Black NiAl coating was deposited on Aluminum 6061 T6 substrate.

III. Methodology And Experimentation

The experimental procedure adopted in this work as follow:

1) NiAl coating on aluminum substrate.

2) The micro-indentation test was carried out using THV-1Digital microhardness tester with a loading range from 0.1N to 10N, The Vickers indenter with the equivalent half cone angle of 68° was used in the test.

TABLE I
Chemical Composition of Aluminum 6061 T6 Alloy

Si	Fe	Co	Mn	Mg	Zn	Cr	Ti	Al
0.68	0.42	0.22	0.11	0.89	0.03	0.05	0.02	balance

TABLE II
NiAl Intermetallic Compound Powder (Wt%)

Nickel	Aluminum
50%	50%

A) Coating Process of Black NiAl coating on aluminum substrate

The Coating Process of NiAl on Aluminum 6061 T6 alloy Specimen must be cleaned for contaminate, soil etc. before processed for coating. Aluminum plates was kept in acetone for 35min and then diluted with water. Black NiAl coating was done on aluminum plate as per the procedure given in [1]. Aluminum 6061 T6 specimen of the size 100 x 50 x 2mm was processed for black NiAl plating. To produce homogeneous coating of thickness 20µm, an electric mixer was used to mix the paint with the 20% NiAl per ml of black paint. A mixture of black paint and NiAl was made by mixing and this mixture was diluted with acetone to ease the application of a uniform layer by immersion or brush painting.

B) Microindentation Process Experiment

A variety of instruments for measuring Vickers hardness are commercially available; some are marketed as complete instruments and others are designed as attachments to a standard microscope. In all instances, a reflected-light microscope forms the basis of the instrument; with a permanent or a detachable indenter head that can be rotated into position in place of a normal objective; the second major addition is a micrometer eyepiece that enables the indentation diagonals to be accurately measured.

The microindentation test carried out on a THV-1Digital microhardness tester as shown in Fig.3 with a loading range from 0.1N to 10N. Four-sided square based Vickers diamond indenter with an apex angle between opposite edges is 136°.

Fig.1 Microhardness Tester

TABLE III

WORKING PARAMETERS FOR THE EXPERIMENT OF MICROINDENTATION

A Method of Work	Loading in point
Indenter	Vickers
Regime of Loading	Loading +10s Dwell+ unloading
Loading Force	Increase from 0.1 to 10 N
Total Loading Time	30 s

Micrometer eyepiece with high power objective was used to check area of specimen which is free from flaws and rotate indenter nosepiece into position. Select suitable load ranging from (0.1-10N) and press cable to initiate loading.

A dwell time was set to 10s. Diagonals after unloading were measured to measure hardness of coated substrate.

The Vickers Diamond Pyramid hardness number is the applied load (kgf) divided by the surface area of the indentation (mm^2).

Vickers Hardness after indentation can be measured from below formula [1]:

$$HV=\frac{F}{A}=\frac{2F\sin\frac{136^\circ}{2}}{d^2} \quad (1)$$

Where,

HV= Vickers hardness

F=applied force in Kgf

A= contact area

d= Arithmetic mean of the two diagonals, d_1 and d_2 in mm

$d=\frac{d_1+d_2}{2}$

IV. FINITE ELEEMENT MODELING

Simulation of elastic-plastic indentation process carried out on 3-D axisymmetric model in order to define axisymmetric model. The model was designated by master and slave surfaces. Material processed for modeling was 3x3x2mm rectangular plate of aluminum 6061 T6 alloy. On top surface of aluminum plate, NiAl coating of thickness 20µm was deposited. The vicker square pyramid indenter was considered as rigid diamond material of angle between opposite faces is 136°. The indentation obtained here was very small as compared to size of the sample. A fine meshing was done near the contact area of coating-indenter and Quadrilateral structure mapped meshing used for indenter. The total number of nodes was 29657 and total number of elements is 14857. Fixed boundary condition was applied at bottom of aluminum plate. Because of geometric symmetry, only one forth part of whole domain considered while modeling indentation process.

Assumption made in contact between two solids and in analysis of the indentation process:

1) The contact between the indenter and coating is frictionless.

2) Force transmitted only in normal direction between the indenter and specimen.

3) Materials are considered as fully homogeneous, free from contaminate and defects.

4) Bonded contact between Coating/substrate interfaces.

In microindentation process, elastic deformation occurs at beginning. To find out occurrence of plastic deformation Von Mises yield criteria can be used. The equation of Von Mises stress is given by the expression [7] as follows:

$$\sigma_{Mises}=\left[\frac{(\sigma_1-\sigma_2)^2+(\sigma_2-\sigma_3)^2+(\sigma_3-\sigma_1)^2}{2}\right]^{\frac{1}{2}} \quad (2)$$

A) Material Properties

TABLE IV

MATERIAL PROPERTIES OF SUBSTRATE, COATING AND VICKER INDENTER

Sr. No.	Name of Part Model	Properties
1.	Substrate	Material= Aluminum Alloy 6061 Elastic modulus=70000MPa Poisson's ratio=0.33 Density=2700 Kg/m^3 Tensile Yield Strength=290MPa
2.	Coating	Material= NiAl Elastic modulus=115000MPa Poisson's ratio=0.32
3.	Indenter	Material= Diamond Elastic modulus=1141000MPa Poisson's ratio=0.07

B) Modeling

In geometric modeling, aluminum 6061 T6 plate modeled in proportion to indenter size, only small rectangular area near the contact of indenter and plate considered in modeling. A plane axisymmetric condition applied in XY and YZ plane. Thickness of aluminum was kept 2mm. coating thickness was 20µm. bonded surface to surface contact was made at the interface of coating and aluminum plate.

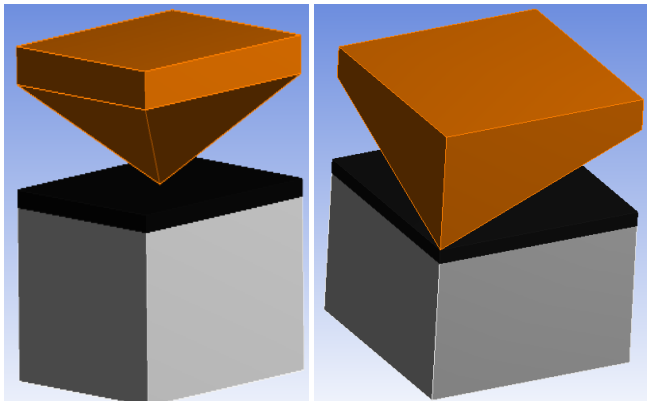

Fig.2. 3D Modeling of Indentation Process

C) Meshing of Model

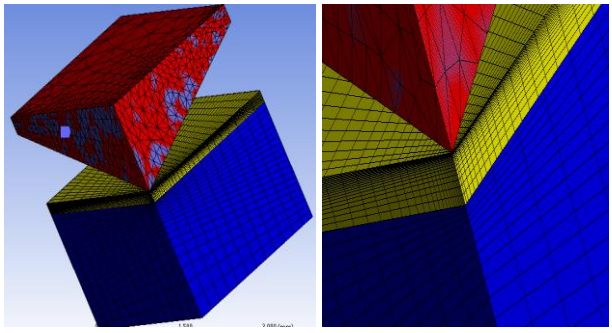

Fig.3. Model Meshing

As shown in Fig. For more accuracy, Fine mesh generated for coating near contact area of indenter and contact and for other region coarse meshing. Mapped quadrilateral face meshing generated for indenter.

V. Results and Dissusion

A) Experimental Results

Microindentation experiment was carried out to find out hardness value of Black NiAl coated Aluminum Substrate. First hardness of bare aluminum sample was finding out by applying load ranging from (0.5-1N) and diagonal impression obtained after indention was measured using microscope. From this hardness value calculated as per formula given in eq. (1). Hardness values at different load are shown in table IV. Average Vickers Hardness Value obtained for bare Aluminum 6061 T6 alloy was 108.58HV.

TABLE V
Measurement of Vicker Hardness for Aluminum 6061 T6 Alloy

Load(N)	Diagonal(µm)	Hardness(HV)
0.5	69	108.9
1	79	118
3	153	114
5	181	117
10	260	85
AVERAGE VICKER HARDNESS		108.58HV

Table VI
Measurement of Vicker Hardness Using Microindentation For Black NiAl Coated Aluminum 6061 T6 Substrate

Load (N)	Diagonal (µm)	Vicker Hardness (HV)
0.1	16.5	269
0.25	22	383
0.5	32.5	349
1	48	322
2	66.5	335
3	101.5	216
5	146.5	172
10	220	145.8
AVERAGE VICKER HARDNESS		273HV

Vicker hardness value obtained for NiAl alloy coated aluminum substrate is 273HV.

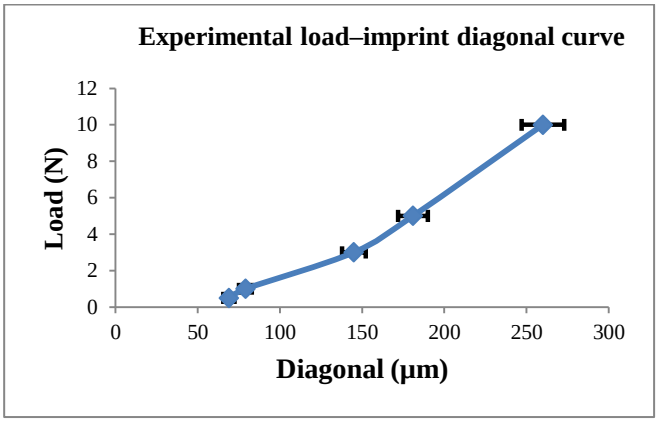

Fig.4 Experimental Load–Imprint Diagonal Curve for Black Painted Aluminum 6061 T6

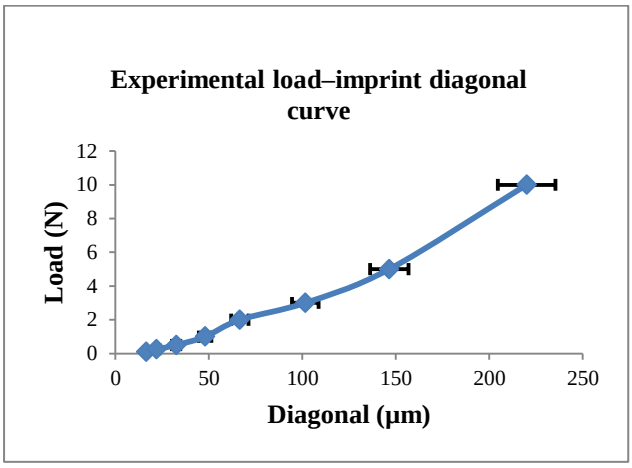

Fig. 5 Experimental Load–Imprint Diagonal Curve for Black NiAl Coated Aluminum Substrate

Fig. 4 and 5 below plotted shows load vs Imprint diagonal plot for black painted Aluminum 6061 substrate and Black NiAl coated Aluminum substrate. Pressing of the specimen with the indenter was realized within 30s, while load applied was from 0-10N. We measured residual imprint's diagonal d through a microscope. Five measurements for each of pointed loadings have been done. From which minimum and maximum values were eliminated.

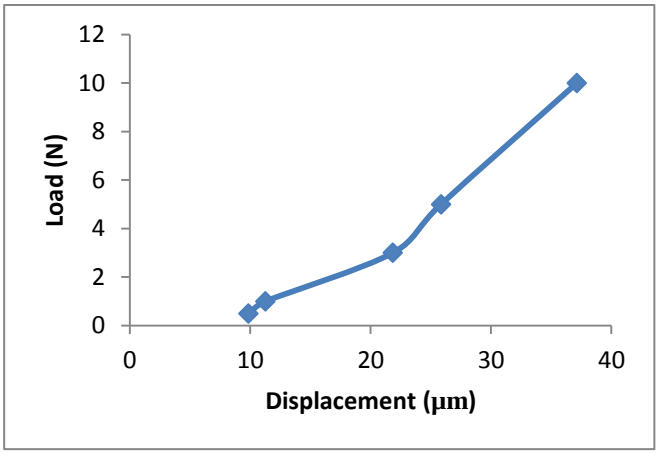

Fig. 6 Experimental Load–Displacement Curve P-h for Black Painted Aluminum 6061 Substrate

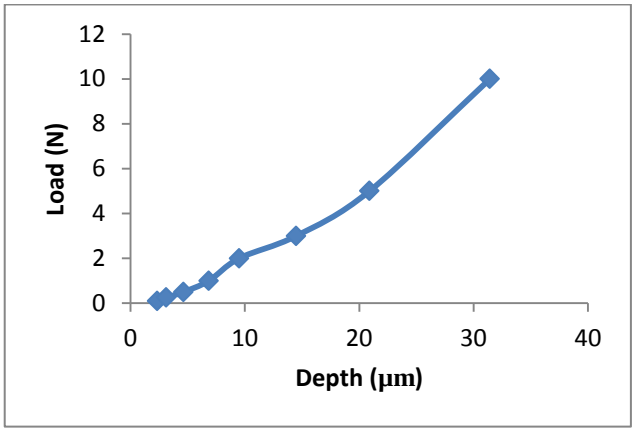

Fig. 7 Experimental Load–Displacement Curve P-h for Black NiAl Coated Aluminum Substrate

The indentation depth was determined according to through the formulae [10]:

$$h = 0.14285d \quad (3)$$

The error associated to the measure of the imprint diagonal d for each of the loadings was calculated through the formulae [10]:

$$d_{average} = \frac{d_{average} - d_{Max\ Deflection}}{d_{average}} \quad (4)$$

Where, $d_{average}$ is the average value of the imprint diagonal. $d_{max\ deflection}$ is the maximum deflection amongst the five measurements. We determined that this experimental error range from 1% to 7%.

From Load –Displacement curve obtained Young's modulus values for Black aluminum and Black NiAl coated Aluminum Substrate are 63Gpa and 74GPa.

B) Finite Element Analysis

By using three dimensional (3-D) models the development of plastic deformation in Black NiAl coated Aluminum substrate was investigated in order to know the better understanding of the plastic deformation behavior in the material. The Total deformation in NiAl coated Aluminum substrate is shown in fig. (4). the plastic deformation in the specimen at the interface i.e. between the indenter and substrate is initiated at the beginning and then propagated as shown in fig. (5), (6). At small indentation depths the Von-Mises stress generated around the indenter tip region and it propagates both vertically and laterally. Three-dimensional model, propagation of plastic deformation gives the better understanding of plastic deformation zone.

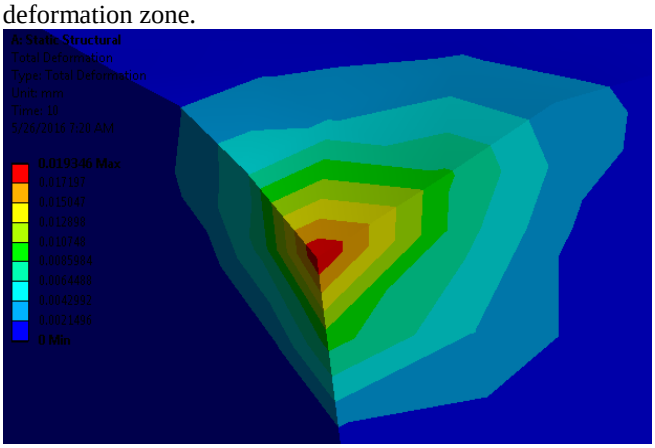

Fig.8. Total Deformation at Indenter and Coating Contact

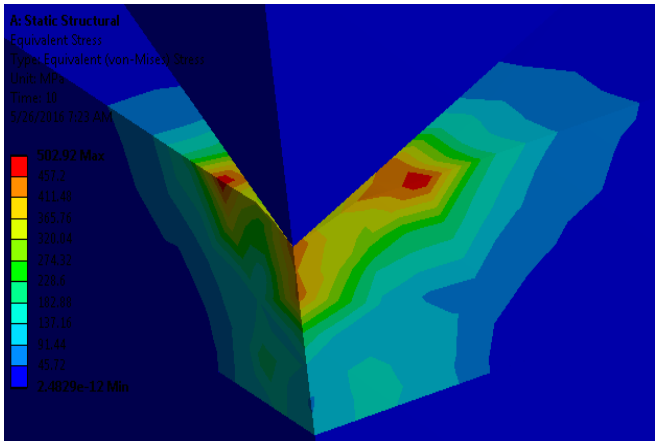

Fig.9. Equivalent Stress at Indenter and Coating Contact

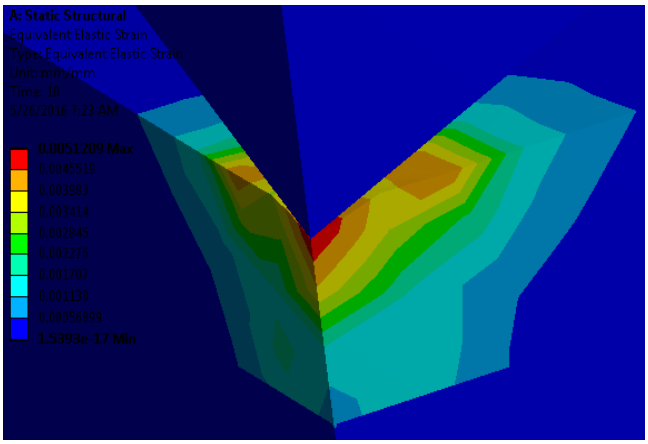

Fig.10. Equivalent strain at indenter and coating contact

Total deformation produced at indenter and NiAl coating contact is 0.019346mm for load of 5N.

Equivalent Von Mises Elastic strain produced was 0.0051209mm.

Equivalent elastic stress developed was 502.92Mpa. Load- Displacement plot for gradually increasing loading and unloading conditions is obtained for NiAl coated aluminum substrate from finite element simulation is shown in Fig.7. From maximum load slope obtained from load-displacement at unloading curve gives value of young's modulus. Young's modulus value obtained for black NiAl coated aluminum is 77GPa.

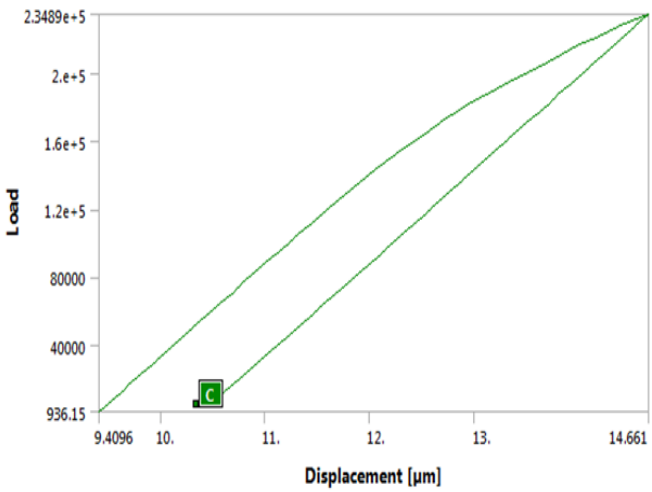

Fig.11. Load- Displacement Graph from FE Simulation

VI. Conclusion

Microindentation experiment was performed on black painted Aluminum 6061 T6 alloy and Black NiAl coated Aluminum 6061 T6 substrate. The NiAl coated substrate was find to be harder than black painted substrate and hardness value ranging from 270-280HV. This concludes as wear resistance property of Black NiAl coated aluminum is better than conventional coating and this coating can be used to replace commercial black paint used for solar collector receivers while operating in high temperature condition.

Three dimensional finite element simulation of microindentation process was carried out on Black NiAl coated Aluminum Substrate using axisymmetric diamond pyramid indenter. The model is capable of simulating the loading and unloading stages of the plastic deformation behavior during the indentation process. Young's modulus value obtained from FE simulation is in good agreement with experimentally obtained young's modulus value. Thus we can measure young's modulus of coated sample using microindentation.

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