Evaluation of surface hardness of NiCr coating using Finite Elements Analysis

Evaluación de la dureza superficial del recubrimiento de NiCr mediante el análisis de elementos finitos

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Abstract

Introduction— To enhance resistance to surface damage of materials due to mechanical actions, there have been created many procedures that allow its modification for different needs. This leads to researches conducted to determine the changes achieved in the properties due to said procedures. One method commonly applied is, for example, physical means of vapor deposition of thin films on a surface. In recent years, many rational and empirical models have been proposed for the study of said properties. One of these models is computational analysis, which allows determining a great number of properties while avoiding applying destructive tests, achieving to reduce experimental time spent and costs of manufacture of test tubes as well as the test itself. In this research, the hardness of a surface coating of Nichrome (NiCr 80-20) was determined with an indentation test modeled in Ansys, based on the finite elements' method.

Objective— To design a computational model that allows determining the surface hardness of material with coating

Methodology— The realization of this project was made with the software for engineering analysis ANSYS, and the model was made based on the Vickers Indentation Test regulation given by the ASTM, which states that the test must be done with a pyramidal diamond indenter, applying forces greater than 1 kgf.

Results— By running the respective numerical analysis for both the substrate and the coating, a surface hardness of 197.5073 VH was obtained for NiCr coating and surface hardness of 160.5809 VH for the S235 Steel (hardness of the interface).

Conclusions— It was determined that the model proposed is correct seeing as the values obtained for the Vickers' Hardness is approximately the same as the experimental value with an error of 0.7501% for the coating layer and 0.2605% for the substrate. It was also concluded that it is possible to use this same procedure to obtain the surface hardness for different materials than those treated in this article by using this tool.

Keywords— Hardness test; finite elements; composite material; coating; simulation

Resumen

Introducción— Para mejorar la resistencia al daño superficial de los materiales debido a acciones mecánicas, se han creado muchos procedimientos que permiten su modificación para diferentes necesidades. Esto hace que se realicen investigaciones para determinar los cambios logrados en las propiedades debido a dichos procedimientos. Uno de los métodos comúnmente aplicados es, por ejemplo, los medios físicos de deposición de vapor de películas delgadas sobre una superficie. En los últimos años se han propuesto muchos modelos racionales y empíricos para el estudio de dichas propiedades. Uno de estos modelos es el análisis computacional, que permite determinar un gran número de propiedades evitando la aplicación de ensayos destructivos, consiguiendo reducir el tiempo experimental empleado y los costes de fabricación de las probetas, así como el propio ensayo. En esta investigación se determinó la dureza de un recubrimiento superficial de Nichrome (NiCr 80-20) con un ensayo de indentación modelado en Ansys, basado en el método de elementos finitos.

Objetivo— Diseñar un modelo computacional que permita determinar la dureza superficial de un material con recubrimiento.

Metodología— La realización de este proyecto se hizo con el software de análisis de ingeniería ANSYS, y el modelo se hizo con base en la norma de ensayo de indentación Vickers dada por la ASTM, la cual establece que el ensayo debe hacerse con un indentador de diamante piramidal, aplicando fuerzas mayores a 1 kgf.

Resultados— Al ejecutar el respectivo análisis numérico tanto para el sustrato como para el recubrimiento, se obtuvo una dureza superficial de 197.5073 VH para el recubrimiento de NiCr y una dureza superficial de 160,5809 VH para el Acero S235 (dureza de la interfase).

Conclusiones— Se determinó que el modelo propuesto es correcto ya que los valores obtenidos para la Dureza Vickers es aproximadamente igual al valor experimental con un error de 0.7501% para la capa de recubrimiento y 0.2605% para el sustrato. También se concluyó que es posible utilizar este mismo procedimiento para obtener la dureza superficial para materiales diferentes a los tratados en este artículo utilizando esta herramienta.

Palabras clave— Ensayo de dureza; elementos finitos; material compuesto; recubrimiento; simulación

I. Introduction

Every material used in the industry has specific properties, by using these, it can be classified and destined for a particular use. However, said properties can't supply every requirement needed for a specific purpose, which leads to the material being modified to improve some of its properties and acquire new advantages.

There are many existing methods for modifying a material, one of them being coatings. Lately, there has been an increasing interest in the deposition of metallic alloys, such as NiCr(80-20), also known as Nichrome, which is composed of an alloy made up of 80% Nickel, 20% Chrome [1], for protection against aqueous corrosion. This is a fairly popular material for coatings on steel as it has been demonstrated to provide wear, erosion, and corrosion protection [2].

After a substrate has been coated with an alloy, tests must be made to determine the final properties of the part. This testing is destructive, but it is useful to determine the behavior the part will have when subjected to different factors, such as temperature, loads, and momentums. One of these properties is *Hardness*. Hardness is defined as the resistance of a material to a local plastic deformation achieved from the indentation of a predetermined geometry indenter onto a flat surface of metal under a predetermined load [3], which in short terms means the capacity of a material to not scratch when subjected to another body's load. To correctly determine these properties in a way that is useful and meaningful, many standardized tests have been proposed, such as the case of Vickers hardness testing.

Among a variety of proposed tests for hardness, Vickers Hardness is one in most widespread use, as it allows for testing in materials with higher hardness than Brinell, and it is simpler than Rockwell indentation, as Rockwell testing procedures change depending on the material, specifically in the kind of indenter used. Meanwhile, the process for Vickers testing requires always the same material and geometry of indenter, regardless of the material to be tested [4]. The conventional procedure of Vickers hardness testing consists of applying a fixed load on a diamond indenter and measuring the dimension of the resultant indentation on the surface of the test material, from which the depth of the indentation and the Vickers Hardness can be inferred [5]. This process implies an economic and time expense as specialized machines for indentation, microscopes and the materials to be indented are required to reproduce this experiment, even more so if the material has post-processing such as coating, in which case the process to achieve said coating also has to be accounted for.

To avoid destructive testing, saving time and expenses, the use of numerical simulation to study the deformation process was proposed, because it seems to be a useful tool for understanding the mechanical phenomena that take place into the material under indentation [6]. This numerical simulation uses the Finite Element Method (FEM), which is a mathematical technique used to perform Finite Element Analysis (FEA) of any given physical phenomenon [7]. This method consists of dividing a continuous geometry of material into discreet points, called elements, each of which can be measured and then, with mathematical analysis, find a trend of behavior for the whole continuous part [8].

For this project, a computational model was proposed, which allows determining the Vickers Hardness for the S235 Steel as a substrate, with NiCr for the coating, using the engineering software ANSYS, using the finite element method.

The proposed substrate for this analysis is S235 Steel, which is a standard carbon-manganese, structural steel, which consists of ~98% Fe and 1.5% Mn [9]. S235 steel is very popular because it's cheap and non-toxic, and it is especially beneficial because it is an efficient anode for the coating process, allowing for better adherence of the coating layer and good advantages in acquired properties after coating [10]. Moreover, its behavior when combined with a layer of NiCr coating is highly beneficial for a high Ultimate Tensile Strength is required, but also corrosion protection is necessary.

The process to carry out the numerical analysis consisted first of determining the requirements for Vickers Testing, which is a process regulated by the American Society for Testing and Materials (ASTM), and then, based on these, designing and setting up a model that was in accordance to said requirements. This includes factors regarding geometries, loads, materials, speeds, or others. Then, the analytical results were compared to those obtained experimentally. This data for the experimental Vickers Hardness was taken from a previous experiment [11], which consisted of performing the experimental indentation testing for this same substrate and coating, and based on results observed from this, proposing a mathematical model of behavior for the interface between the coating and the substrate. Finally, conclusions were drawn to indicate whether the model proposed was able to successfully determine the analytical Vickers Hardness of the aforementioned materials.

II. Methodology

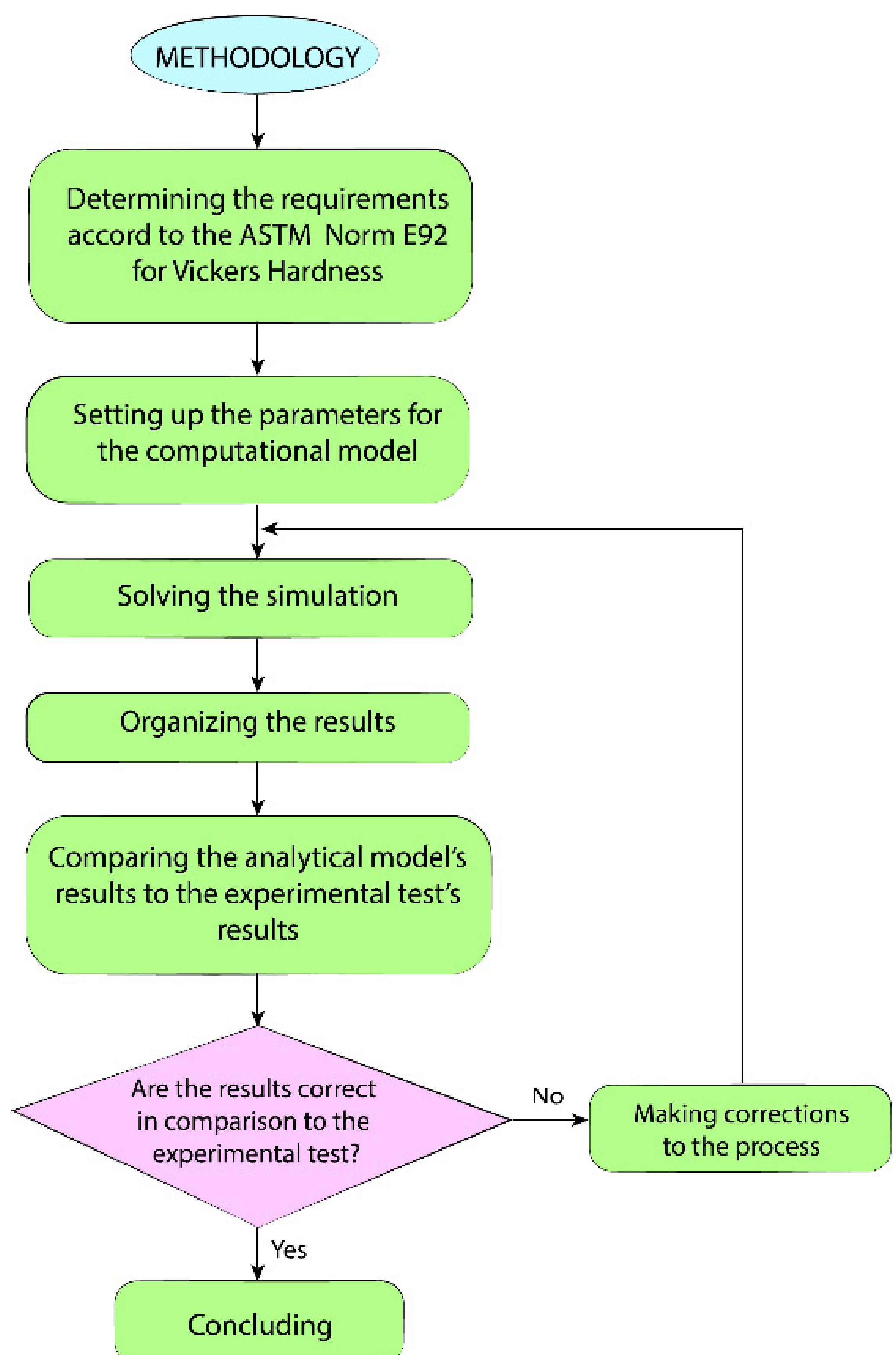

Fig. 1. The methodology followed for the realization of the simulation.
Source: Authors.

A. *Vickers test according to the ASTM E92 norm*

Vickers testing is a useful methodology for the realization of experiments that intend to analyze the hardness, microhardness, and macro hardness of a material, by applying an indentation of a specific depth into the material that is to be tested. This test implies a series of technical specifications and requirements for its correct fruition, which are explained further on to be applied in the simulation carried out.

1) *Force Ranges*

The materials used range in Vickers Hardness from 160 to 200 VH [11]. For this range of Vickers Hardness, the force applied for testing must be greater than 1 kgf, which is equivalent to 9.81 N [12]. This classifies the test as micro indentation. Vickers macro indentation is defined as that which uses loads greater than 1000 gf and its indentation speed must be of a maximum of 0.2mm/s.

2) *Properties of the test tube*

There isn't a specific standardized geometry the test tube should have; however, some guidelines have been set to guarantee the correct execution of the experiment.

The surface of the test tube must have a minimal quantity of defects. Moreover, each test tube must be used only once per test.

In computation, this can be represented by a smooth test tube surface.

- The surface of the test tube to be indented must be perpendicular to the indenter's axis, and the face opposite to the surface to be indented must be preferably parallel to it.
- The test tube must be fixed at the time of testing.
- The thickness of the test tube should be at least ten times the depth of the indentation. This thickness can be expressed (1):

$$h_v = 0.143 * d_v \quad (1)$$

Where is the depth of the indenter and is the length of the imprint's diagonal.

To ensure that the former requirements are fulfilled, a test tube was designed, whose dimensions can be considered infinite in comparison to the imprint left by the indenter,

3) *Characteristics of the Indenter*

A Vickers Hardness Indenter type A was used (Fig. 2), which has the geometry of a pyramid with a squared base, its material being polished diamond, with face angles of 136°0' ± 30'.

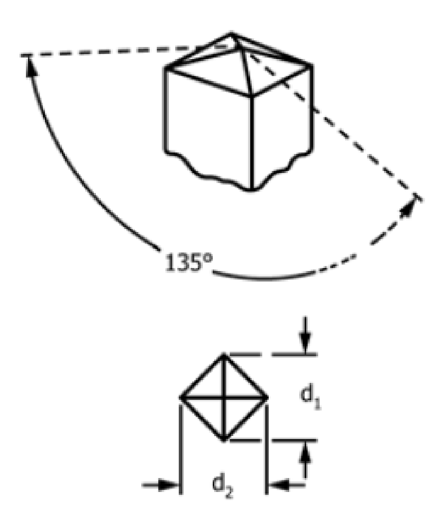

Fig. 2. The geometry of the Vickers Indenter Vickers.
Source: ASTM E92 [12].

4) *Determining Vickers Hardness*

Vickers Hardness for macro indentation must be determined in terms of *gf* and μm according (2):

$$HV = 1854.4 \times \frac{F_{(gf)}}{{d^2}_{V_{(\mu m)}}} \quad (2)$$

Where d_V is the length of the imprint's diagonal.

B. *Computational Model*

The computational simulation was done by using the Engineering Software Ansys Workbench, with a student license, where the parameters to be explained in the following section were taken into account to ensure the correct implementation of the test.

The test was done implicitly, meaning that the problem was considered quasi-static, ignoring the influence of acceleration during the indentation, which coincides with the parameters established by Vickers Testing, given that it restricts the speed at which the test tube must be indented.

1) *Physical properties of the problem*

The properties shown below are the same that were inputted into Ansys for each of the materials tested.

- *Substrate*

The substrate used is S235 Structural Steel, whose properties can be found in Table 1.

Table 1. Properties of S235 Steel.

Density [kg/m^3]	7850
Coefficient of thermal expansion [× 10^{-5} K^{-1}]	1.2
Young's Modulus E [GPa]	200
Poisson's ratio	0.3
Creep resistance S_y [MPa]	235
Ultimate Tensile Strength S_{ut} [MPa]	360

Source: [13].

- *Coating*

The coating used is a NiCr 80-20 alloy, whose properties are as shown in Table 2.

Table 2. Properties of NiCr.

Density [kg/m^3]	8558
Coefficient of thermal expansion [× 10^{-5} K^{-1}]	1.4
Young's Modulus E [GPa]	218
Poisson's Ration	0.31
Creep Resistance S_y [MPa]	724
Ultimate Tensile Strength S_{ut} [MPa]	344

Source: [14].

The thickness of the coating used is 0.49 mm [11].

- *Indenter*

Because the indenter is made from diamond, it can be said that it is sufficiently rigid to suffer a minimal deformation that can be ignored. As such, the indenter, in the simulation, is modeled as a rigid body.

2) *Model*

- *Coating*

The coating was applied by using the Surface Coating function in Ansys. Since the purpose is to determine the superficial hardness, this was applied to the test tube's face which comes into contact with the indenter, as shown in Fig. 3.

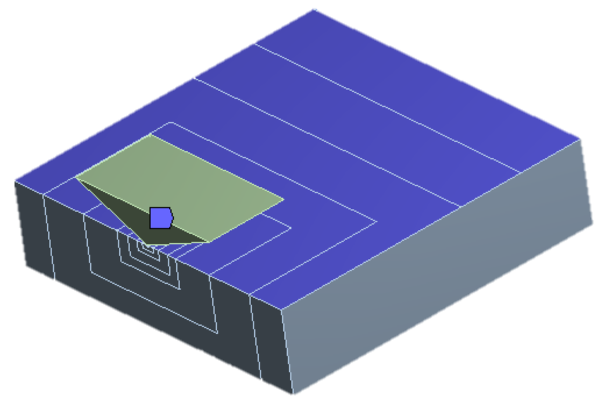

Fig. 3. The surface where the coating was applied.
Source: Authors.

- *Symmetry*

To decrease the time spent in solving and to use fewer elements, only half the test tube and indenter were modeled, and by applying the symmetry function, the analysis for the other half was achieved. Symmetry was applied to the faces in red as shown in Fig. 4.

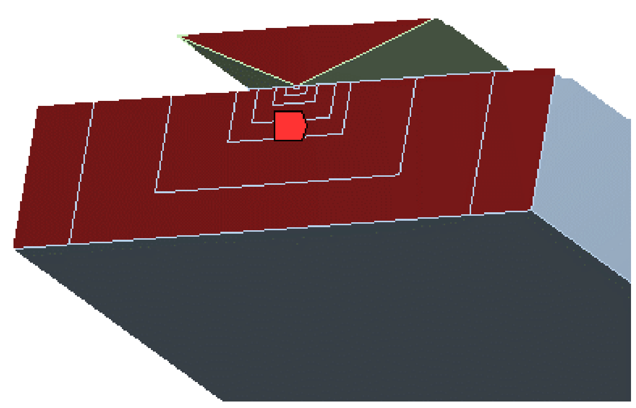

Fig. 4. Face where the symmetry was applied.
Source: Authors.

3) *Connections*

Translation and rotation of the indenter were limited so that the movement would only happen in the vertical direction. Due to the indenter being a rigid body, it is not possible to use the boundary condition *Displacement* provided by Ansys, as this is only available to use for flexible bodies. In its place, a *Body-Ground* joint, of general type, was used, where translation in the X and Y axis were fixed, as well as rotation in the 3 axes, leaving only available translating movement in the Z-axis (vertical axis).

For contact between the indenter and test tube, a type *of Bonded* contact was established, which is a type o contact that doesn't allow separation or relative gliding between the two bodies. Moreover, the contact was defined with *Asymmetric behavior*, which is what is mandated by Ansys for the contact between flexible and rigid bodies [15].

The contact was defined in the faces as seen in Fig. 5 where the contact surfaces are signal in red, while the target surfaces are signaled in blue. Once again, these were selected this way because, by Ansys' parameters, the rigid body should always be declared as the target.

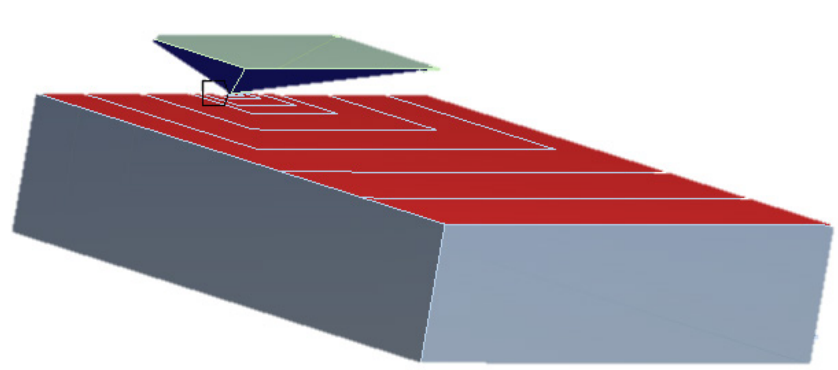

Fig. 5. Contact Faces.
Source: Authors.

4) *Mesh*

A mesh with varying sizing was used, having a total of 19 197 elements, and configured in such a way that the number of elements increases as it gets closer to the indentation area, wherein the regions with the highest density mesh are found.

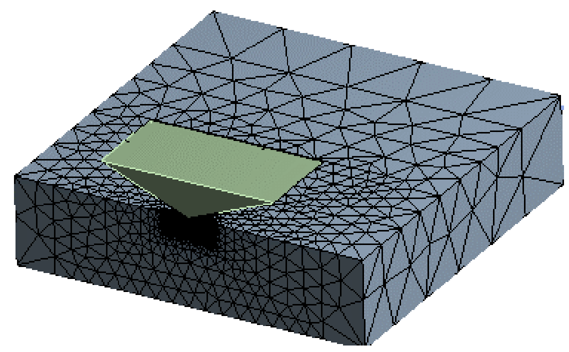

Fig. 6. Meshing used for the simulation.
Source: Authors.

5) *Boundary conditions*

To fix the position of the test tube, a *Fixed Support* was applied to the inferior face, as can be seen in Fig. 7, effectively fulfilling the aforementioned condition of the test tube having to be fixed at the time of indentation.

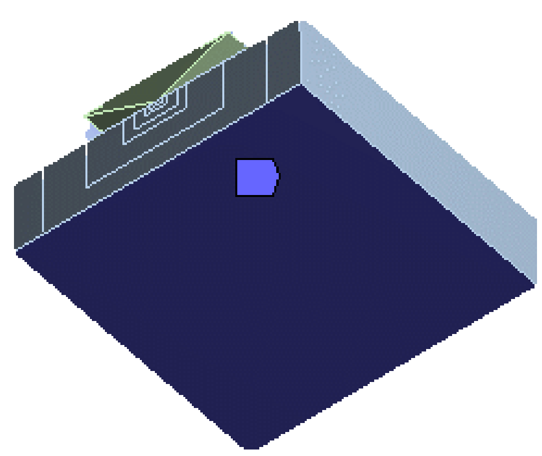

Fig. 7. Fixed Support applied to the inferior face.
Source: Authors

Different ranges of loads were applied, according to what was set in section **A. Force Ranges**. These forces were applied to the upper face of the indenter (Fig. 8) using the function *Remote Force*. In Ansys, when working with a rigid body, as is the case for the indenter, mathematically it is interpreted as a point, which is why a force can't be directly applied to it. However, Remote Force allows creating a coordinate system based on the geometry of the rigid body, which in turn allows for a force to be applied to a specific face of it [15].

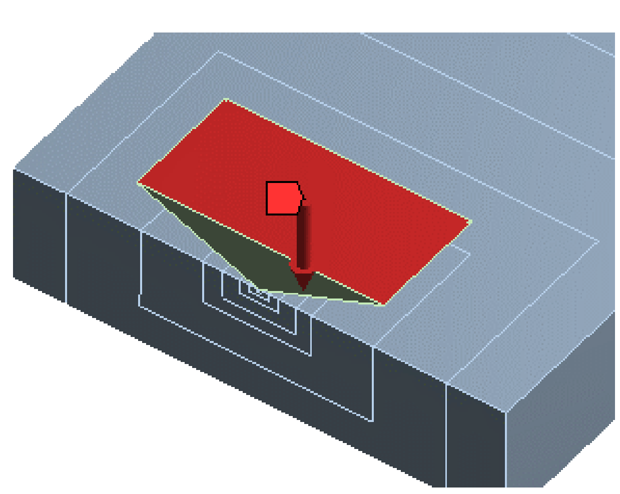

Fig. 8. Remote Force Applied to the Indenter.
Source: Authors.

6) *Solving*

Total deformation was measured in mm, and the Vickers Hardness was determined according to the following (3):

$$d_v = 2y tan\theta \times 1000 \quad (3)$$

Where,

d_v is the diagonal imprint left by the indenter, shown in Fig. 2, in mm,

y is the total deformation in μm and,

θ is half the indentation angle, meaning 67.5°.

This DV is then introduced in (2) effectively obtaining the hardness of the material.

The error in the results obtained is determined by comparing the analytical values obtained with the experimental ones. The values for the experimental Vickers Hardness test were acquired from previous research by [11], which consisted of performing the experimental indentation testing for these same substrates and coating, and based on results observed from this, proposing a mathematical model of behavior for the interface between the coating and the substrate. In this research project, it was found that the experimental Vickers Hardness for the S235 Substrate was 161 HV, and for the NiCr coating of 199HV.

The error was determined according to the following (4):

$$\%E = \frac{|VH_1 - VH_2|}{VH_2} \times 100 \quad (4)$$

Where,

VH_1 is the hardness obtained using the simulation done in Ansys and,

VH_2 is the experimental hardness according to [11].

This procedure was repeated 10 times, varying the applied load. The range of tests was chosen like this because it made sense to keep it the same as in the experimental test, as this project attempts to replicate the experimental test analytically so that the results can be compared with it.

The error was determined for each case to ensure each result was correct. Finally, an average for Vickers Hardness was determined, by using (5):

$$\overline{VH_1} = \frac{\sum_{i=1}^{N} VH}{N} \quad (5)$$

Where N is the number of tests, in this case, 10. This hardness was then compared to the experimental one, by once again using (4), and if the error is less than 5%, it is considered a minimal enough error that it can be concluded that the model designed is correct.

III. Results and Discussion

By solving the simulation, it was initially found that the results obtained analytically were significantly different from those obtained experimentally. From this, it was concluded that the tribological behavior of the pair substrate-coating is independent, because the deformations are different for each one, as they are different materials. Taking this into account, separate meshing was done individually for both substrate and coating, and the hardness was calculated again.

A load from 2kgf up to 2.040 kgf was applied. The results obtained for the substrate are shown in Table 3, and for the coating in Table 4.

Table 3. Vickers Hardness obtained for the Ni-Cr Coating.

Cycle	d_v [μm]	$F[kgf]$	VH_1	%E
1	134.59241	2.000	204.7351	2.8819
2	135.32633	2.005	203.0267	2.0224
3	136.06025	2.010	201.3431	1.1775
4	136.79417	2.015	199.6840	0.3437
5	137.52809	2.020	198.0487	0.4781
6	138.26684	2.025	196.4230	1.2950
7	139.00559	2.030	194.8206	2.1002
8	139.74431	2.035	193.2410	2.8939
9	140.29477	2.038	192.0797	3.4772
10	140.48792	2.040	191.6707	3.6831

Source: Authors.

$$\overline{VH_1} = 197.5073 \quad (6a)$$

$$\%E = 0.7501\% \quad (6b)$$

Table 4. Vickers Hardness obtained for S235 Steel.

Cycle	d_v [μm]	$F[kgf]$	VH_1	%E
1	148.9675	2.000	167.1283	3.8064
2	149.3214	2.005	166.7531	3.5734
3	150.3705	2.010	164.8442	2.3877
4	151.3080	2.015	163.2130	1.3745
5	152.2570	2.020	161.5846	0.3531
6	153.3070	2.025	196.7732	0.7620
7	154.6932	2.030	157.3102	2.29180
8	155.5573	2.035	155.9506	3.1353
9	156.2003	2.038	154.8973	3.7905
10	156.1553	2.040	154.3513	4.1296

Source: Authors.

$$\overline{VH_1} = 160.5809 \quad (7a)$$

$$\%E = 0.2605\% \quad (7b)$$

The percentage error obtained for the Vickers Hardness, though small, is a consequence of inconsistencies between the real test and the simulation, however, the simulation which was designed in this paper can be considered as assertive and those inconsistencies can be ignored, as the error obtained was of less than 1%, confirming the validity of the analytical model.

Many uncertainties happen when doing mathematical simulations, which contribute to there being an error from experimental results. These uncertainties are the results of limitations in existing mathematical models, or even in the technology level required to be able to solve these models in a way that can be automated so it doesn't have to be done manually, as that would be too time-consuming and mathematically complex. These limitations include the ability to precisely represent in mathematical terms the interstitial behavior of the interface between two materials, as this behavior changes depending on the coating process, and for the moment, contact types have to be relied upon to mimic these as closely as possible.

This is similar to another limitation regarding contact between the indenter and the test tube, which is to say, limitation in contact between to bodies, which for the moment is not capable to realistically show computationally the rough or wrinkled surfaces coming into contact with each other, with relatives speeds to one another, it can only ever do an approximation to these by considering factors like arbitrary frictions and using correction factors.

IV. Conclusions

The analytical Vickers Hardness obtained for the S235 Steel, which was the substrate, was of 160.5809 Vickers Hardness, with an error of 0.2605% in comparison to the experimental Vickers hardness, which was of 161VH. In the same way, the analytical VH obtained for the NiCr coating was 197.5073 VH, which has a 0.7501% error when compared to the 199 HV which was the experimental one. Thereupon, it can be concluded that the model proposed is correct and the analytical Vickers Hardness was successfully determined using numerical simulation.

The tribological behavior of the pair substrate-coating is independent because, in each, different deformations are produced by the same load, instead of deforming as one, even when in bonded contact.

The use of the software Ansys can be recognized as an appropriate tool for simulation as it is designed to offer concrete functions to achieve static simulations which allow determining physical properties of materials, and what's more important, obtaining results that are correct and trustworthy. Therefore, it can be concluded that it is possible to apply this same procedure to determine the hardness of other materials different from the ones analyzed here, by following the model designed, as well as properties different from hardness, by using this software.

Looking forward, it is important to work on developing said mathematical models or to work on developing the technology capable of solving those in existence that can't be applied yet due to their complexity. By doing this, the numerical simulation will reach new lengths allowing for more complex, useful, complete, and realistic simulations to be made, allowing in turn for greater technological development.

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