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Effect of Friction on the Estimation of Thin Sheet 0.8%CNT Cu-Ti Brinell Hardness Using Axisymmetric Finite Element Simulation of Ball Indentation

Abdulaziz S. Alaboodi

College of Engineering, Qassim University, Saudi Arabia
alaboodi@qec.edu.sa

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Abstract. In this paper, the effect of friction coefficient on the estimation of the Brinell Hardness of thin sheet 0.8%CNT Cu-Ti is investigated using an axisymmetric finite element model (FEM) of ball indentation. The study conducted by analyzing the sheet material in the elastic-plastic region by using the ball indentation loading-unloading curve. The results indicate that variation of the friction coefficient has a direct effect on the estimation of the Brinell Hardness.

Keyword: Friction Coefficient, Ball Indentation, Axisymmetric Finite Element, Brinell Hardness

1. Introduction

In order to reduce wear and minimize friction, there have been advancement in research and development of new materials to satisfy the need of thin, hard coating layers, which are progressively used in different engineering applications. Indentation test is one of the nondestructive testing methods that is available to obtain an impression of the material mechanical properties with thin thickness. Researchers presented a different procedure of using indentation result analysis to transform load-penetration depth curves into stress–strain curves or to obtain its hardness properties directly [1].

Many researchers used ball indentation in different applications. For instance, a numerical model was established for contact fractures subjected to both cyclic and monotonic contact loadings using FE methods to simulate crack growth or even fatigue [2]. Similarly, a parametric study was carried out on an axisymmetric FE model to study the influence of different factors on the indentation force response [3]. The indentation test could be applied in the area of components life assessment in industry, as a non-destructive test that could be implemented on site [4].

The continuum damage accumulation theory has been adopted to estimate the area reduction rate using a ball indentation test. Thus, an identification of the failure point in the indentation surface is done by transforming the multiaxial strain data of the indentation test to a tensile uniaxial strain [5]. Indentation method has been widely used and adopted in the description of the mechanical properties of materials [6]. Its fascination stems totally from the obvious - that mechanical behavior of materials can be determined instantly from displacement measurements and indentation load without the necessity of using the hardness conventional methods to measure the hardness of materials. Nowadays, high-technology equipment can smooth the measurement of mechanical properties to a small scale of micrometer and nanometer [7]. For that reason, the technique has grown to be an essential method for figuring out the mechanical behavior of thin films and microstructural features [8]. Films with miniature dimensions, such as one micrometer, are now readily determined. Moreover, the method can be used to characterize the mechanical behavior of nanostructure films. Improvements have been provided in the method's accuracy and the range of its usage in the field due to experiential work in developing equipment and techniques [9].

For instance, Micro Electro Mechanical system (MEMS) was investigated using the Nano indentation to evaluate the MEMS load-depth curve of bridge structures by assessing the critical elastic-plastic bending deflections [10]. There are thrilling methods for calibrating indenter based on the area functions and load [11]. Nano-indentation has become the common way to determine the characteristics of the mechanical properties, especially when the materials have a complex stress-strain. Calculating the Nano-indentation by experimental work is complex, costly, and requires technicians with advanced skills [12]. On the other hand, the FE method provides an easy and cheap way for complex materials to be analyzed. Mechanical properties, such as hardness and yield strength, could be predicted exactly from known values of stress-strain data [13]. In order to develop a software to be used for portable instrumented indentation test, the advantages and disadvantages of available analytical methods were reviewed, and ideas were put forward to improve them [14]. Similarly, it has to restrict the materials in which there is no time-dependent fracture, e.g. viscoelasticity or creep. The most commonly used technique is Nano-indentation, which could be used to quantify the hardness and Young's modulus of a material from one cycle duration of loading and unloading curve. This could be obtained from the indentation load and displacement data. The ball indentation test involved one indentation cycle on a sample surface using a ball indenter at the same deformed location. The cycle consisted of a sequence of loading and unloading [15]. Improvement of nano-scale characterization can have impact for design [16]. The CNTs reinforced Cu-Ti composites were fabricated by powder metallurgy process to improve the interface bonding strength of composites [17]. The load–displacement curves from the simulation with different COFs have been analyzed for an aluminum single crystal [18]. Moreover, a combined experimental and modelling study of indentation damage test on thin-film stacked structures [19]. More review about nano-indentation and its usefulness in material characterization are available in [20].

The effect of friction on estimating the mechanical properties of film or coating through indentation technique is not investigated in depth in the literature. Hence, the present work introduces a parametric study of the ball indentation technique and inverse analysis using an axisymmetric FE model. This study aims at investigating the effect of the friction coefficient on the estimation of the Brinell Hardness of thin sheet Cu-Ti CNT. The method used to achieve the objective is using FE simulation model of an indentation process of reinforced CNT/Cu-Ti using ANSYS software.

2. Modeling

Due to the indenter geometry, the similarity is not retained with the increase of penetration. Subsequently, mean pressure increases with the increase of load. This principle was used as the basis for the ball indentation test. During the test, as multiple indentations occur, the load and geometry of indentation start to vary progressively. The indentation depth and load were measured continuously during the test as shown in Fig. 1. The indentation load–displacement parameters are illustrated in Fig. 2.

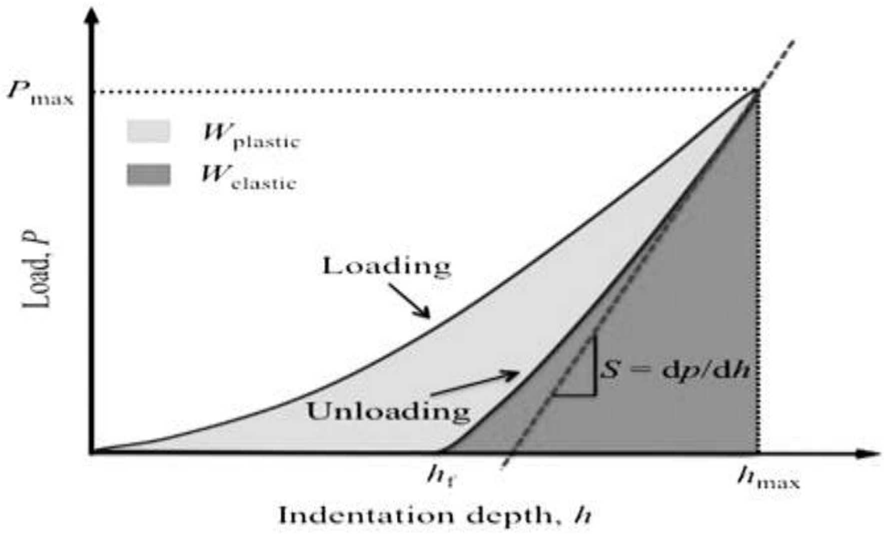

Fig. (1). Load and unload indentation P_{max} is the maximum indentation load, h_{max} is the maximum indentation depth, h_f is the final depth, the elastic strain energy $W_{elastic}$ is the area under the unloading curve, and the indentation absorbed energy $W_{plastic}$ is the area under the loading curve.

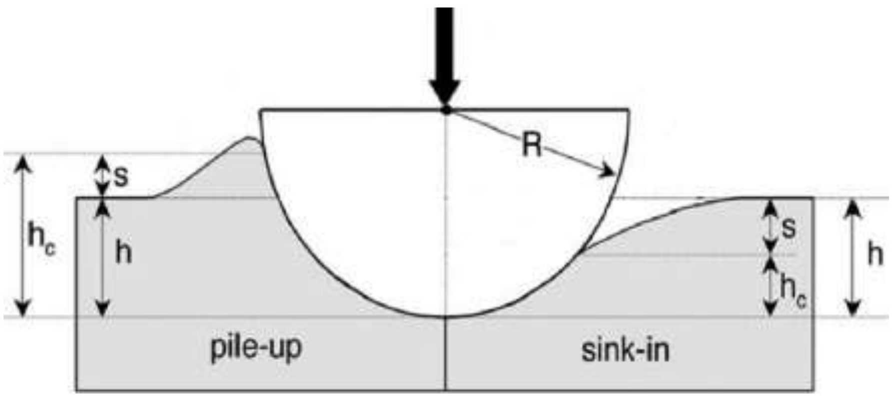

Fig. (2). Cross section of an indentation profile showing the ball radius (R), contact depth (h_C), pile-up depth (s) and indentation depth at maximum load (h)

2.1 Material Modeling

The selected material for the FE indentation modeling and simulation is the well dispersion of CNTs with 0.8% CNTs/Cu-Ti with mechanical properties deduced using a tension test [17]. As shown in Fig. 3, the elastic properties are Elastic modulus of 15 GPa, Poisson's ratio of 0.33, the yield strength of 408 MPa and the ultimate strength 569 MPa. Ball indenter material is the tungsten carbide with a modulus of elasticity of 650 GPa, a compressive strength of 5.1 GPa, a tensile strength of 450 MPa and Poisson's ratio of 0.21.

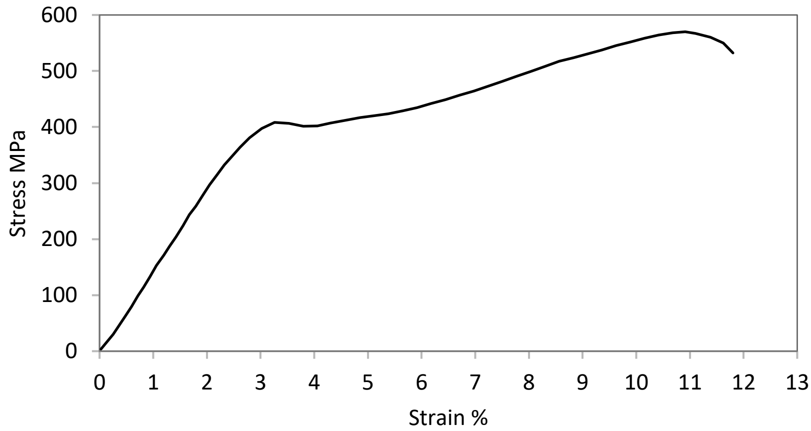

Fig. (3). The stress-strain curve of 0.8% CNT/Cu-Ti [17]

2.2 FE Modeling

An axisymmetric model was used to simulate the ball indentation problem. A 2D plane strain model was not suitable for this problem because the indenter would be assumed as a cylinder instead of a ball, while the axisymmetric model mimics the ball geometry. The geometry consists of one-layer material with 2 mm thickness and 4 mm width and indenter of 1.75 mm radius. A load was applied by introducing an upward displacement to the spacemen while fixing the indenter. Displacement control is more stable than load-control in contact numerical convergence.

The target and contact surface were selected as the top surface of work piece and the bottom surface of indenter, respectively. The behavior of the contact was selected as frictional contact with a frictional coefficient varying from 0 to 0.5 with an increment of 0.1. The Coulomb model was utilized to define the friction between contacting lines-where they could withstand shear stresses. The bottom of the work piece was fixed. The indenter was incrementally vertically displaced vertically downwards from 0 to 0.2 mm. The maximum displacement is 10% of the sample thickness. Subsequently, the indenter retrieved back. The loading and unloading cycle was performed in 20 steps. Each step has sub-steps controlled by the software until convergence. Mesh sensitivity analysis was utilized to confirm a mesh-insensitive result, and the final mesh consisted of 980 nodes and 302 elements as shown in Fig. 4.

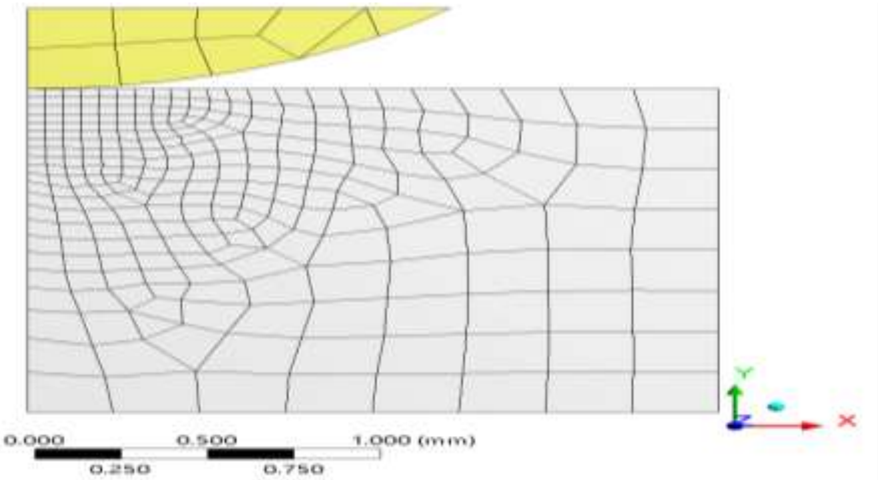

Fig. (4). Mesh of the axisymmetric model**.**

3. Results and Discussions

The procedure used in this work is a combination of FE modeling and inverse analysis to study the friction coefficient effect on the estimation precision of the elasto-plastic mechanical properties of the sample material using the ball indentation technique and inverse analysis. The displacement depth is presented in Fig. 5 versus the force vertically applied on the indenter during the loading and unloading cycle for the two friction coefficients of 0 and 0.7. The sample with the frictional surface exhibits a maximum force of about 233 N higher than that of the smooth sample. In the case of f =0, the maximum force was 2351 N with a displacement depth of 0.4 mm and the permanent depth after unloading was 0.2975 mm, see Fig. 6. In contrast, at the case of f =0.7, the maximum force was 2584 N with a displacement depth of 0.4 mm and the permanent depth after unloading was 0.2885 mm, see Fig. 6.

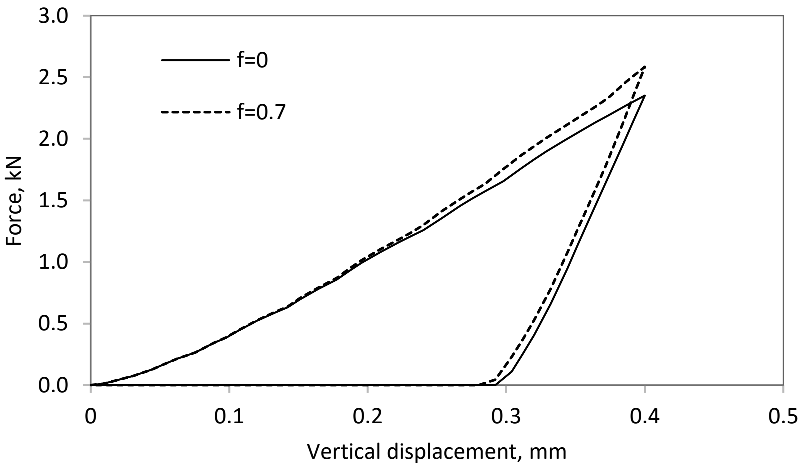

Fig. (5). Displacement depth versus the vertical force applied on the indenter during a loading and unloading cycle for two friction coefficients, *f*.

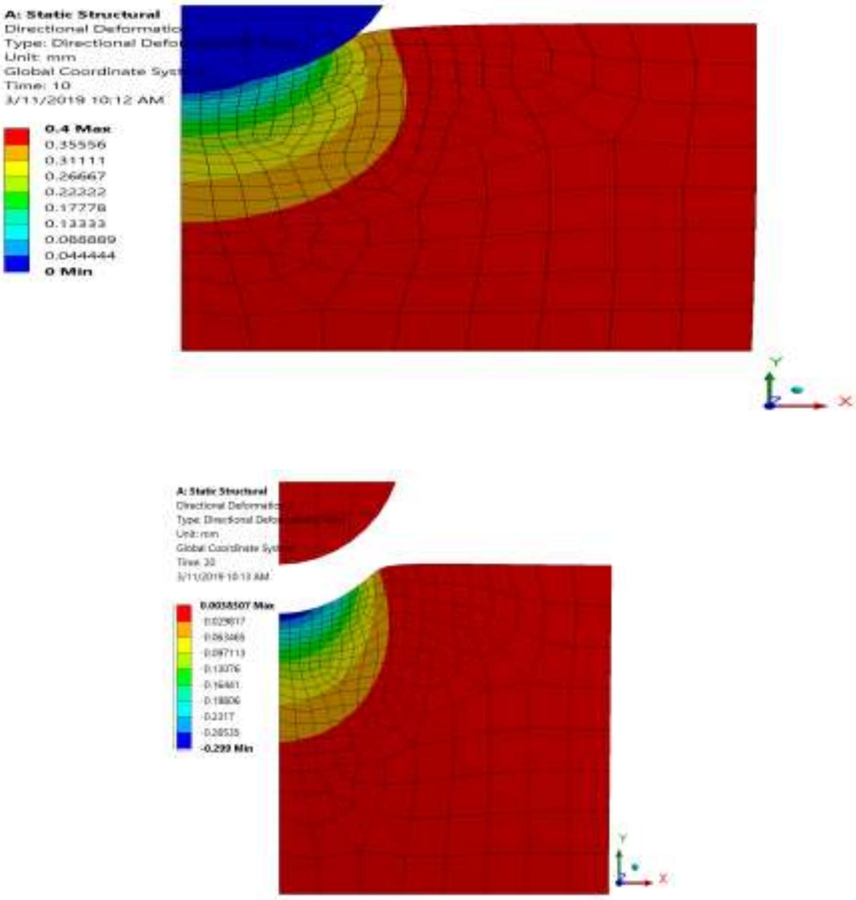

Fig. (6). Displacement at loading and unloading the indenter; friction coefficient = 0.5

The variation of the friction coefficient, f, from 0 to 0.7 gives the force reaction behavior as shown in Fig. 7 which demonstrates an increase in the reaction force with the increase in f until the value of f reaches 0.4 beyond which the reaction force remains constant. On the contrary, the retraction displacement decreases with the increase in f. However, beyond f =0.2, the retraction displacement remains the same as presented in Fig. 8.

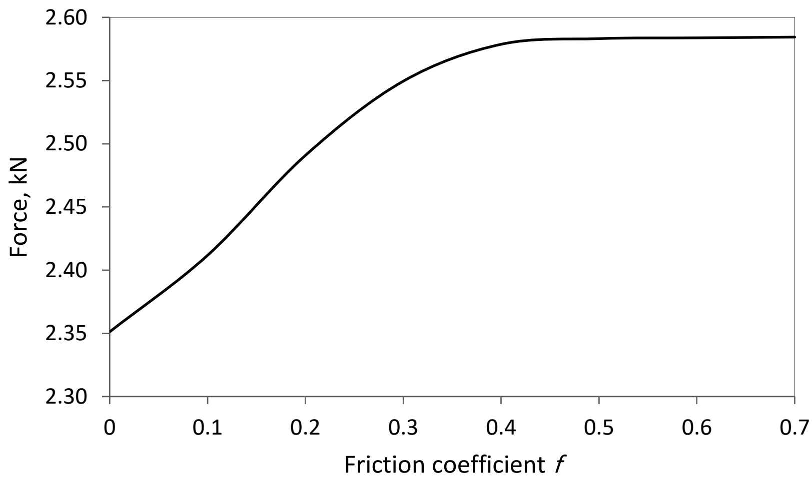

Fig. (7). Reaction force versus friction coefficient

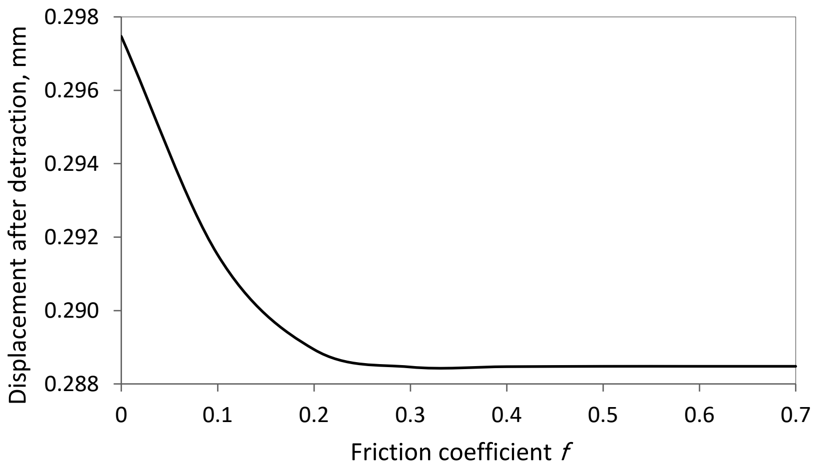

Fig. (8). Displacement versus friction coefficient

The Brinell hardness number (BHN) could be predicted by the following equations:

$$BH = F / \pi D hf \qquad (1)$$

where F is the applied force in N, D is the indenter diameter = 1.5 mm and hf is the unloading final displacement. The use of Equation (1) calculates the hardness and, thus, leads to Fig. 9 to show the effect of varying friction coefficient f on hardness estimation. Fig. 9 shows the variation of the Brinell hardness, BH, of the sample material with the variation of f. The behavior of the BH variation is similar to that of the reaction force. The variation in the BH ranges between HB 1800 and HB 2040 kN/mm2.

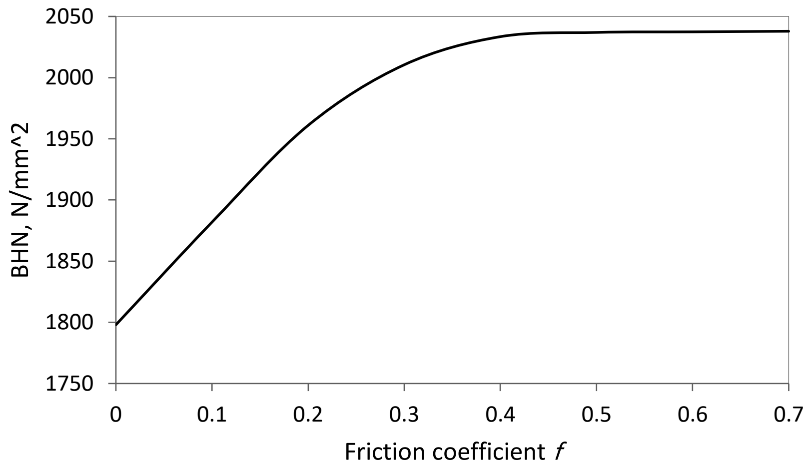

Fig. (9). Hardness versus friction coefficient

It is reported in [17] that the hardness value of 0.8% CNTs/CuTi is 216 HV in Vickers hardness scale. The equivalent is 2000 N/mm2 in Brinell hardness scale. The range of harness shown in Fig. 9 is between HB 1798 and HB 2038, with a maximum variation of 10.14%. Moreover, it can be indicated that, the friction coefficient equal to 0.28 corresponds to the value of hardness of 2000 HB.

The reason of such variation in hardness estimation with the variation of friction coefficient is that as friction is increased and the amount of sink-in Fig. 2 becomes smaller, the volume of material that originally displaced sideways shall be accommodated over a larger region underneath the indenter. This phenomenon increases the size of the plastic zone in solids exhibiting pileup as shown in Fig. 10.

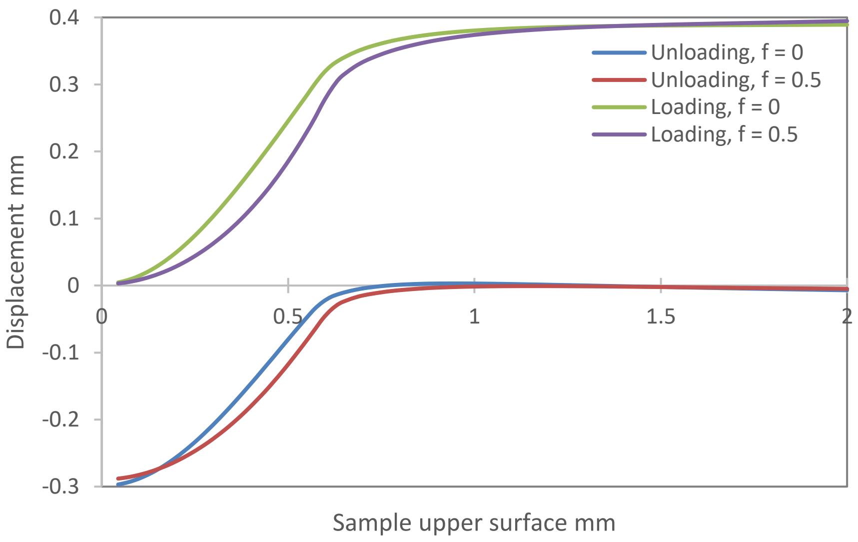

Fig. (10). Sample upper surface displacement at loading and loading with friction coefficient of f =0 and 0.5

5. Conclusions

The friction coefficient effect on the estimating of hardness test was investigated using FE method. A ball indentation loading and unloading test was simulated to obtain Brinell Hardness of thin sheet 0.8%CNT Cu-Ti. It was indicated that the suggested method could determine the material hardness using indentation loading and unloading displacement curves of the indenter. Moreover, the friction coefficient has a direct effect on the hardness estimation. The present FE results demonstrate good agreement with published experimentation. Furthermore, the indenter-specimen friction coefficient of the conducted experiment can be predicted from the FE results.

6. References

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تأثير معامل الاحتكاك على تقدير الخواص الميكانيكية للرقائق النانوية Cu–Ti ذات الصفائح الرقيقة باستخدام الوخز الكروي والعناصر المحدودة المتماثلة حول محور

عبد العزيز سليمان العبودي

كلية الهندسة– جامعة القصيم– المملكة العربية السعودية

alaboodi@qec.edu.sa

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ملخص البحث. في هذه الورقة، تم دراسة تأثير معامل الاحتكاك على تقدير صلابة برينل للرقائق الرقيقة من الأنابيب النانوية الكربونية Cu-Ti باستخدام نموذج العنصر المحدود المتماثل حول محور للوخز الكروي. يتم ذلك عبر تحليل المنطقة المرنة والبلاستيكية باستخدام منحنى تحميل وتفريغ الوخز الكروي. وتشير النتائج إلى أن التغيير في معامل الاحتكاك له تأثير مباشر على تقدير صلابة برينل.