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# Finite element simulation of nano-indentation experiment on aluminum 1100

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ABSTRACT

The main purpose of this study is to investigate the nano-indentation test method and validation of its finite element simulation. In the first stage, the nano-indentation experiment was performed on aluminum 1100 series by using Triboscope system and Berkovich indenter and the Young's modulus and hardness of the material were determined. In order to verify the results of nano-indentation experiment, the uniaxial tensile test was also performed on the same material and its Young's modulus was measured. Good agreement was found between the values of Young's modulus obtained from the two test methods.

Then in the second stage, the nano-indentation process on aluminum 1100 was simulated by an axisymmetric finite element (FE) model. Using the same projected area to depth function as the standard Berkovich indenter, a conical rigid indenter with half-angle of 70.3° was considered in the simulation. The results showed that the load–displacement curve obtained from the finite element simulation of non-sharp indenter was in very good agreement with that obtained from the nano-indentation experiment. Based on the load and displacement data obtained from the finite element simulation, the material hardness was also calculated. The difference between the hardness values obtained from the finite element simulation and the nano-indentation experiment was negligible.

## 1. Introduction

Different mechanical test methods are available to measure the mechanical properties of materials. The results of these test methods are used in engineering design and also as a basis for comparing and selecting materials. Uniaxial tensile test is a conventional method for measuring the mechanical properties like Young's modulus, yield strength, strain hardening, toughness and tensile strength. Conventional mechanical test methods are often destructive and need relatively large amount of sample materials.

As an alternative and appropriate method to measure the mechanical properties of both bulk materials and thin coatings, the nano-indentation test has been used recently by many researchers for different types of materials [1–8]. The nano-indentation test uses a standard method in which an indenter tip is driven into specific sites of the sample material by applying an increasing normal load. According to the load–displacement data which is recorded during the test by high resolution instruments, the mechanical properties of specimen including Young's modulus, hardness and elastic–plastic deformation are determined [1,9–11]. Since in the nano-indentation test the indentation depth is in the order of nanometer and the residual indentation diameter is often in the order of nanometer, this test needs less sample material, decreases costs and is independent of the specimen geometry.

Finite element (FE) analysis is widely used for modeling different engineering problems. For indentation processes, the finite element simulation can be employed for investigating the stress and strain fields under the indenter tip which are used to determine the basic mechanical properties of materials. Some researchers have performed finite element analysis for studying the indentation process [12–14]. Considering an appropriate value for the dimensions of sample material, indenter and indentation depth, finite element modeling can also be used for simulating the nano-indentation process [15–19]. Some investigators have compared the results obtained from the FE simulation of nano-indentation and from the experiment to validate finite element modeling of the nano-indentation process [15,17,20,21]. They have shown that the finite element simulation could be an appropriate method for determination of material hardness.

In this study, both the uniaxial tensile test and the nano-indentation experiment are performed on aluminum 1100 to compare and validate the values of Young's modulus obtained from these two different experimental techniques. The nano-indentation test is also simulated by finite element method to determine the stress field under the indenter and to calculate hardness of aluminum

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1100. Then, a comparison between the results of nano-indentation test and FE simulation is performed to validate the procedure used for finite element modeling of nano-indentation experiment on aluminum 1100. It is also explored how the roundness of indenter tip can affect the results obtained from the finite element simulation of the nano-indentation experiment.

## 2. Experimental method

The uniaxial tensile test and nano-indentation experiments were performed on aluminum 1100 series specimens. For each experiment appropriate specimens were prepared and the test procedures were accomplished as described below.

### *2.1. Uniaxial tensile experiment*

The uniaxial tensile test was performed by universal testing machine (SANTAM, IRAN) based on ASTM E8/E8M-09 standard [22]. According to this standard, five dog-bone specimens of aluminum 1100 series were prepared and stretched uniaxially with a constant rate until final fracture occurred.

### *2.2. Nano-indentation experiment*

The nano-indentation test was conducted using a Triboscope system (Hysitron Inc., USA) and a Berkovich indenter, which is primarily used for bulk materials. The testing instrument was calibrated according to the ISO 14577 standard [23]. A cubic specimen of 3 mm thick with the section area of $10 \times 10\ \mathrm{mm}^2$ was prepared from aluminum 1100 material. It is known that the surface finish has a significant influence on the nano-indentation test results. Preparation of the test surface shall be carried out in such a way that any alteration of the surface hardness (e.g. due to heat or cold-working) is minimized [24]. Therefore, the surface of specimen was ground with 400–2500 grit sandpapers and then polished by alumina suspension. The roughness values of the tested sample at the indentation regions were examined using atomic force microscopy (AFM).

Previous studies [25,26] have shown that in the nano-indentation experiment, the mechanical properties of materials are affected by the penetration depth of indenter and in most cases after a depth of 200 nm the measured properties are almost stable. Indeed, based on the ISO 14577 standard the indentation depth should be deep enough to minimize the surface effect. Meanwhile, the indentation depth should also be less than 10% of the film thickness when the sample is mounted on a hard substance. In the current study, the maximum indentation depth of 210 nm was achieved by applying an indentation load of 450 μN. In the nano-indentation test, the mechanical properties of sample could be calculated by relations which have been derived from the theory of contact mechanics and the Oliver–Pharr's method [27].

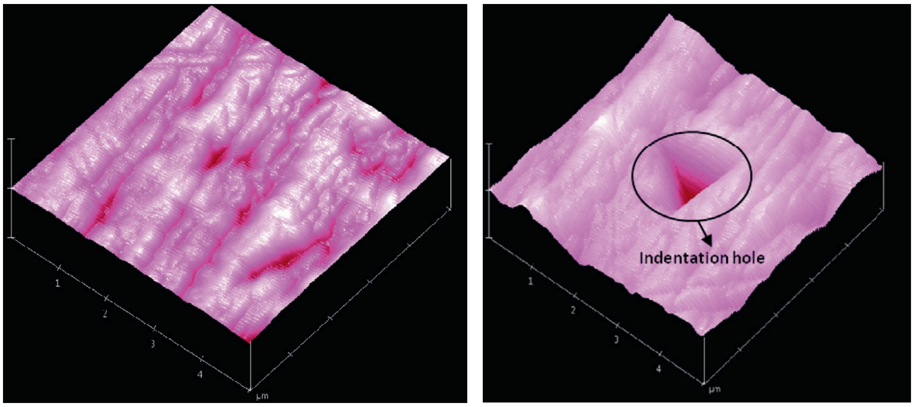
According to the method described above, several indentations on the randomly selected sites of the sample were performed at a temperature of 23 °C in order to obtain five nearly repeatable load–displacement curves from the experiment. Then the average of these curves was used for analysis of experimental results. The AFM images were also used for the surface analyses before and after the indentations (Fig. 1a and b).

## 3. Finite element modeling

A 2-D axisymmetric model was employed for finite element simulation of the elastic–plastic behavior of material in the nano-indentation process. A conical rigid indenter with half-angle of 70.3° was used in the axisymmetric model which has the same projected area to depth function as the standard Berkovich indenter. Fig. 2 shows the schematic representation of indenter and specimen used in the finite element model. Lichinchi et al. [15] have shown that there is very little difference between the results obtained from the 2-D axisymmetric and 3-D finite element simulations of the nano-indentation experiment by Berkovich indenter. Considering that a 2-D simulation requires less computational time and is more convenient than a 3D model, an axisymmetric model was used in this study.

The specimen was meshed with 805 four-node bilinear axisymmetric quadrilateral, reduced integration elements as shown in Fig. 3. A fine mesh was used under the contact area and near the tip of the indenter to study the stress distribution under the indenter more accurately. In order to reduce the computational time, coarser mesh was used further away from the indenter tip. Nonlinear geometry option was used in the finite element simulation. As mentioned earlier, to simulate the nano-indentation process the sample height was considered to be about 50 times larger than the maximum indentation depth.

The mechanical properties obtained from the uniaxial test on aluminum 1100 (as described later in Section 4.1) were used in finite element simulation of the nano-indentation test. A piece-wise linear stress–strain curve obtained from the results of uniaxial tensile test was used in the finite element modelling. According to [28], kinematic hardening material behavior was considered for aluminum 1100.



(a) Before nano-indentation test (b) After nano-indentation test

**Fig. 1.** AFM images of aluminum 1100 surface before and after the nano-indentation test.