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Modeling effect of surface roughness on nanoindentation tests

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Abstract

Surface roughness is a commonly used criterion for characterization of surface quality in a machining operation. In the study of micro-scale mechanical properties of machined surface and cutting tool with nanoindentation, prefect surface finish on the test specimen is often required for the reliable result. However, the prefect surface finish is often difficult to obtain from the machining operation due to the limitation of the cutting tool geometry and machining dynamics. In presented paper, the effect of surface roughness on nanoindentation measurement was investigated by using finite element method. A 3D finite element model with three levels of surface roughness was developed to simulate the load-displacement indentation process with a Berkovich indenter. The material used in the simulation is AISI 316L stainless steel and it was modeled as an elastic-plastic von Misses material. Three levels of surface roughness, R_a, are used in the simulation, including 2 *nm*, 20 *nm* and 37 *nm*. The mechanical properties were calculated by combined simulation with the Oliver-Pharr method. The hardness and reduced modulus from the simulation was found to decrease with an increase of roughness. The scatter of load-depth curves and deviation of hardness and reduced modulus are affected by the changing of roughness. The height of pile-up was little affected by the surface roughness from the simulation. Combined effect of indenter tip radius and surface roughness was also investigated.

Keywords: Nanoindentation, Machine operation, Surface roughness,Young’s modulus, Hardness

1. Introduction

It is well known that the Nano-scale mechanical properties have significant impact on the performance of the machined component, such as fatigue, wear, corrosion resistance [1]. In the study of micro-scale mechanical properties with nanoindentation test on machined surface and cutting tool, prefect surface finish on the test specimen is often required for the reliable result [2, 3]. However, prefect surface finish is often difficult to obtain from the machining operation due to the limitation of the cutting tool geometry and machining dynamics [4]. In presented paper, the effect of surface roughness on nanoindentation measurement was investigated by using finite element method. In nanoindentation, calculation of mechanical properties, such as hardness and Young’s modulus, is based on the measurement of load P and contact area, A_{proj}, during the depth-sensing indentation [4]. The contact area is not measured directly in the indentation experiment but calculated from the depth of contact and the indenter geometry. Since the contact area is obtained indirectly from the depth of penetration in sample material, the natural roughness of the specimen surface can cause errors in the determination of area in the contact between indenter and sample. This specially applied in the coating and thin film indentation, such as coated cutting tool, mold and die, in which the indentation depth is limited by their thickness [3]. To simplify the calculation, the assumption of smooth surface and continues contact in the whole process of indentation is often made in the calculation of mechanical properties [4]. Alternatively, much larger indentation depth is required in the test, such as in Vickers indenter test, it always requires the contact depth larger than 20 times of roughness to eliminate the effect of roughness to some extent [1].

The effect of roughness on indentation can be found in many previous investigations but they were mostly focused on the spherical indenter [4-8]. The

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maximum asperity height and the contact radius was investigated in spherical indenter test by [4] and it was reported in this research that the roughness has a significant effect when small load was applied in the test and effects, however, are less severe for sharper indenters. Bobji et al. [5] studied effect of macroscopic scale roughness (R_m is about 1 *mm*) for different shape of asperities and he found that both the Young's modulus E_{IT} and hardness H are sensitive to roughness. Furthermore a liner relationship between the effect of H and E_{IT} also was reported. In the study made by Walter et al. [6], with using 2D FE model, it was observed that the increase of roughness causes a greater scatter of elastic modulus, E_{IT}, in an elastic deformation material with a spherical indenter. With the method of molecular dynamics, the research [7] intended to give a physical understanding of the vicinity of the contact area indented by the rigid indenter which is difficult due to the inhomogeneity of the surface properties. It is suggested that the existence of a surface step makes the load needed to nucleate the dislocations decrease significantly. According to this study, the roughness is studied by experiment, the sample is single-crystalline aluminium, it is prepared by electro polishing, and the roughness is measured by the atomic force microscopy (AFM). The displacement burst is sensitive to the roughness of the sample; the initial displacement load is decrease with the increased roughness [8].

Results from previous investigation based on the FEM simulation indicated the significant effect of roughness on nanoindentation test. However, these models were focused on the 2D axisymmetric model, the spherical indenter and full elastic material, in which the true scenario of the indentation measurement was significantly simplified. Moreover, the geometry effect was often ignored in the most research. This paper presents 3D finite element model with Berkovich indenter to simulate the effect of roughness on nanoindentation test. To provide better understanding of roughness effect in nanoindentation, the elastic-plastic deformation behaviour and different indenter tip radii were also introduced in this paper.

2. Simulation of roughness

The 3D roughness model was created to simulate surface roughness effect on a nanoindentation. It is difficult to create the 3D roughness model directly in Abaqus CAE. The approach presented in this paper used the program in Matlab to generate a 3D surface roughness with designed values and then mapping the surface roughness into the Abaqus to create the FE roughness model. A flat surface was created in $N \times N$ nodes with Matlab program [9] [10]. The height of each node was changed randomly based on the calculation from following equation (1)-(3) to meet the designed roughness values.

$$R_a = \frac{1}{n}\sum_{i=0}^{n} |\, y(i)\,| \qquad (1)$$

$$y(i) = z(i) - R_m \qquad (2)$$

$$R_m = \frac{1}{n}\sum_{i=0}^{n} z(i) \qquad (3)$$

Where R_a is the arithmetic average of absolute values, and it is common called roughness; n is the amount nodes of the surface; $y(i)$ is the distance between the peak or valley to the mean value; $z(i)$ is the height of each node; R_m is the mean value of all nodes height; and $z(i)$ is generated by a random function in Matlab software. The new surfaces were created with required surface roughness through the iteration calculation.

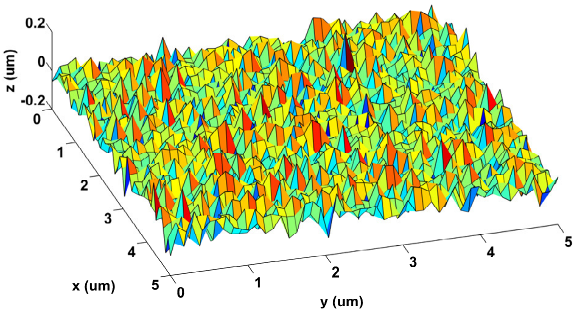

Fig. 1.Simulated roughness surface with R_a=37 *nm*

The interpolation at the top surface nodes positions were done by a Matlab program, it is shown in Fig 1. First, a sample model was generated in Abaqus CAE. Then, Matlab code was written to find the top surface nodes, and change the height of top surface nodes to the requirement of the roughness profiles. Finally, the changed top surface nodes were put into the input file and simulation performed in Abaqus CAE. The roughness of 2 *nm*, 20 *nm* and 37 *nm* models were shown in Fig 2. In the generation of surface roughness, the minimum element size was larger than the minimum asperities of the sample's roughness. The maximum asperities of sample roughness were smaller than 3 times of the minimum element size.

3. Finite element model

The nanoindentation test on bulk materials with isotropic elastic-plastic properties is simulated using Abaqus/Explicit 6.11 with uniaxial stress-strain data as an input. In this study, AISI316L is chosen as the reference material since it is a single face material with simple structure. The material model used for the test specimen is Von Misses plasticity with isotropic hardening. The material parameters are the following: elastic modulus E = 210 GPa, yield stress σ_y = 1.1 GPa and Poisson's ratio v_S=0.28 [11, 12].

The conical rigid indenter is used in the model with semi-angle of 70.3°, which corresponds to a Berkovich indenter. The indenter was considered as a rigid body, since the elastic modulus of the indenter exceeds that of the specimen, and also due to the fact that this study do not focus on the deformation of the indenter. The element type used is a modified 10-node second-order tetrahedral element (C3D10M), and the number of elements is 2313. The specimen is modeled with 321632 continuum 3D, eight-node reduced integration elements (C3D8R). The model assembly, in its initial state, can be seen in Fig 2. A much finer mesh was applied around the contact area and near the tip of the indenter.

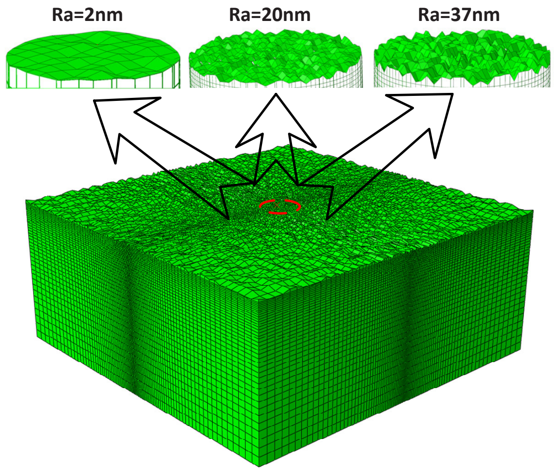

Fig.2. 3D FE roughness model

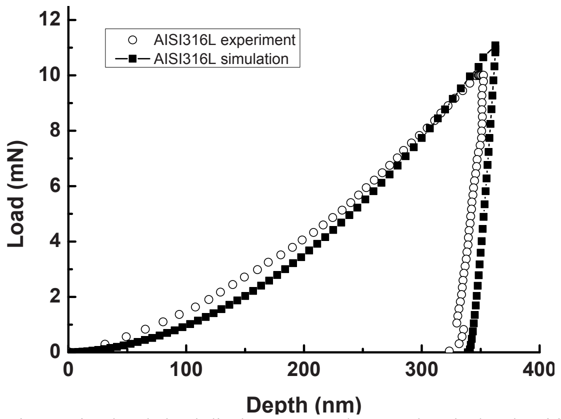

Fig.3. Simulated load-displacement values and calculated with experiment of AISI316.

The nanoindentation process was simulated both during the loading and unloading steps. In the loading process, the simulation was performed to a depth of 362 nm, 10 mN in the vertical direction and during the process of unloading, the indenter tip returns to the original position. The controlled displacement method was applied in the simulation. The contact constraint is defined by the master and slave surfaces. In the model the indenter is the master surface and the specimen is the slave surface. A fix boundary condition is applied on the bottom of the specimen. The validation of the FE model was examined with the experimental data of AISI316. The results obtained from the FE model was compared to the experiment performed with AISI316, as presented in Fig 3. A good agreement between results from FE simulation and experiment were obtained.

4. Results and discussion

4.1 Effect of roughness

For each roughness, fifteen simulations were conducted and it is found that the amplitude of surface roughness has effect on the contact area between indenter and specimen material. The indentation position is randomly selected in the simulation. When the indenter is located on a peak the contact area is larger than the ideal case and when the indenter is located on a valley it is smaller. Since the controlled displacement method is applied in the simulation, the initial position of the indenter tip plays an important role. The zero point is set at the displacement when the load is over zero initially.

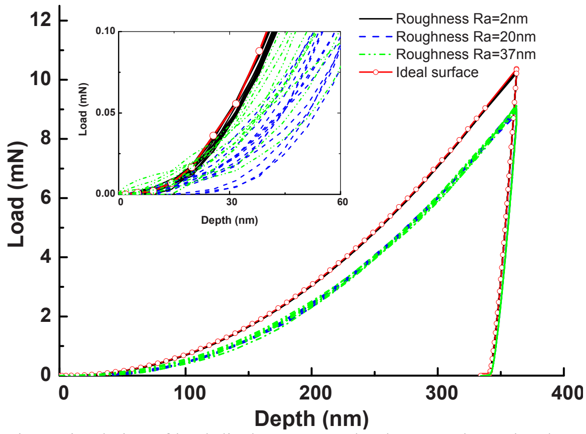

Fig.4. Simulation of load-displacement under three roughness levels

The load-displacement curves for indention depth if 362 nm are shown in Fig 4. The difference in loading process is clearly seen, whereas the unloading part of the curves shows no significant difference for the three types of roughness. The initial load-displacement curves for different roughnesses are studied and the effect of roughness is clearly observed in Fig 5, where the load-displacement curves for each roughness is presented for displacements between 0-60 nm. As expected, the data scatter is increasing with the increasing roughness. This data scatter due to high surface roughness is a frequently encountered problem when trying to characterize the mechanical properties in shallow nanoindentation depth.

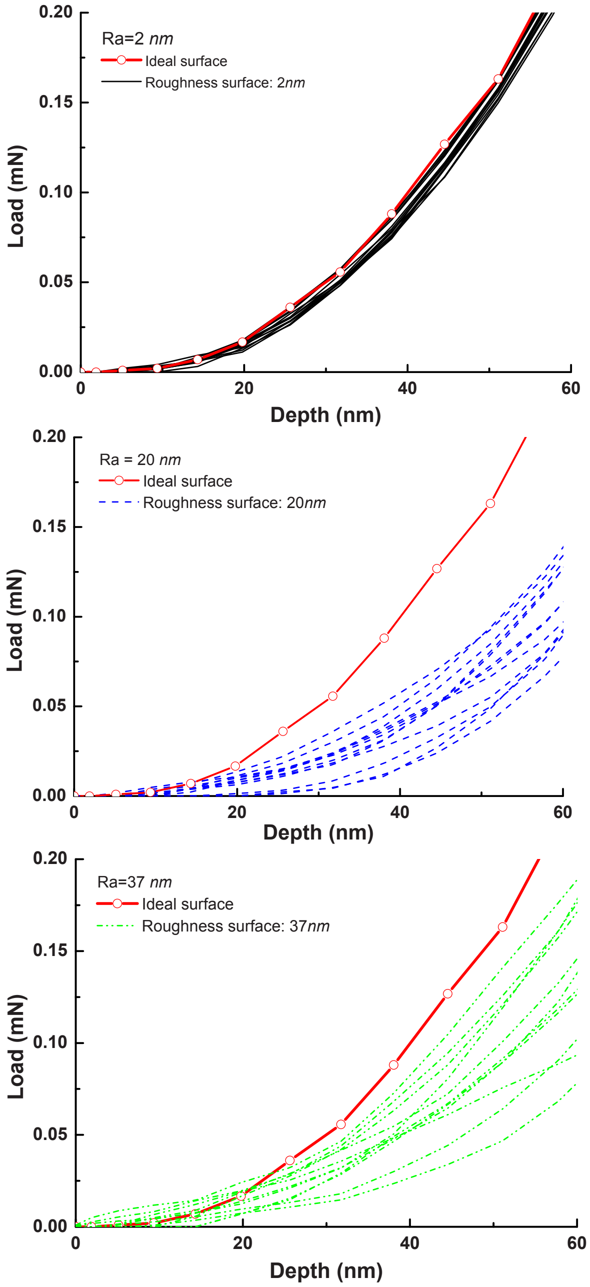

Fig.5. The scatters of loading under different roughnesses levels in indentation

The strain distribution in the loading process is shown in Fig 6. The surface roughness distribution gives rise to the asymmetric distribution of the strain in the beginning of the nanoindentation, but after a certain depth the strain distribution becomes axisymmetric. Fig 6 shows the strain distribution in ideal model and roughness model. On Fig 6(a) the strain distribution when the indentation depth is 249 *nm* in 20 *nm* roughness model, is seen, Whereas Fig 6(c) shows the strain distribution at the same depth of ideal model. As it is seen in the roughness model the disorder of the strain distribution is increased. Fig 6(b) and Fig 6(d) are the comparison when the indentation depth reached the maximum value of 362 *nm*. As seen, the disorder of the strain distribution still exists in the roughness model.

The reduced modulus and hardness are calculated for different surface roughness using the method described in [13]. The calculated values are presented on Fig 7. In the ideal model, i.e. the model without roughness the reduced modulus is 197.5 *GPa*, and hardness is 2.3 *GPa*.

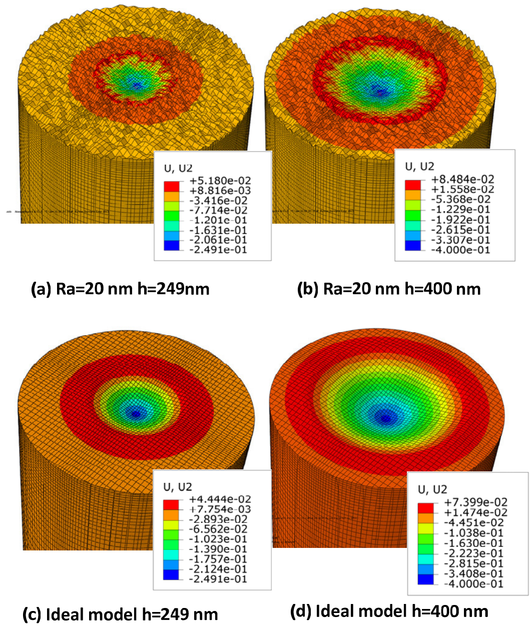

Fig.6. Comparison of strain distribution in the indentation process under rough (a, b) and smooth surface (c, d)

From Fig 7, it is seen that the increase of the roughness results in decreasing of reduced modulus and the hardness. The scatter of hardness and reduced modulus is increasing with the increased roughness. According to the simulations of $R_a = 2nm$, the results are matched with the results from the simulations of ideal surface, but when the roughness is larger than 20*nm*, the effect of roughness cannot be acceptable. The deformation profiles for the three roughness models are seen in Fig 8. The pile-up effect is clearly observed here but there is no significant difference between the different roughnesses. However, the project area is not the same and when the roughness is increasing, the project area is decreasing.

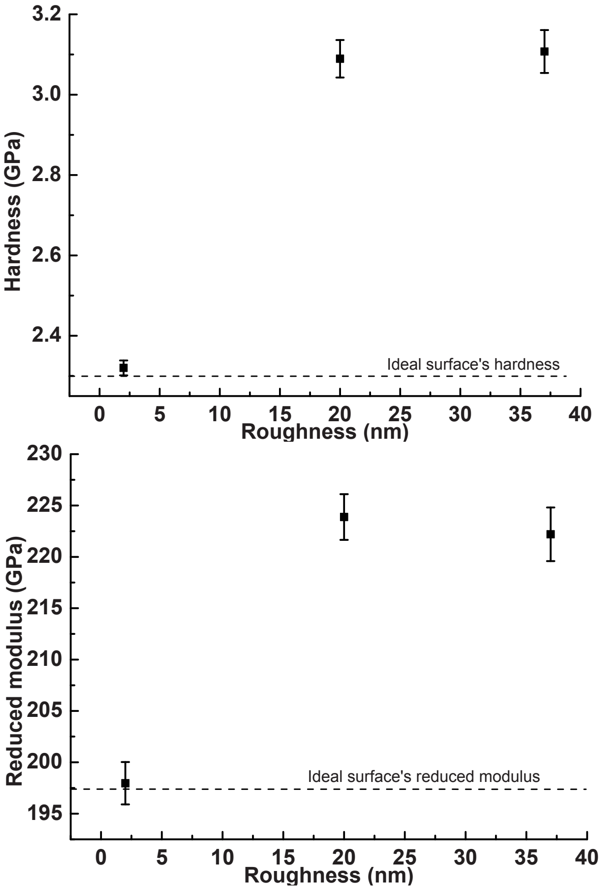

Fig.7. Reduced modulus and hardness under different roughnesses

4.2 Effect of tip radius in roughness

The geometrical effects of the tip radius were studied in our previous work [13]. Here, the effect of the tip radius combined with the roughness is investigated. Fig 9 shows the scatter of roughness for three values of the tip radius: 35 *nm*, 80 *nm*, 120 *nm*. It is shown that the radius does not have a significant effect on the scatter of the load-displacement curves, but the load is increasing with increased tip radius in loading. The reduced modulus and hardness are calculated for the roughness of 20 *nm* and the three different tip radii, 35 *nm*, 80 *nm* and 120 *nm*, see Fig 10. The figure also shows that the effect is around 19% in hardness which is around 15% in Young's modulus. The sensitive of radius in roughness is decreasing with an increased radius. It does not have significant effect in the scatter of hardness, Young's modulus and Load-depth curves. Thus the tip radius has little effect when roughness is introduced in the model.

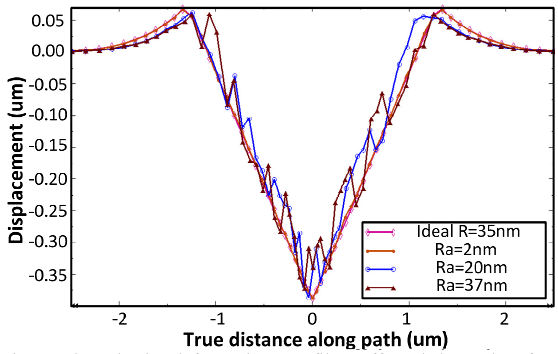

Fig.8. The plastic deformation profiles affected by subsurface roughness.

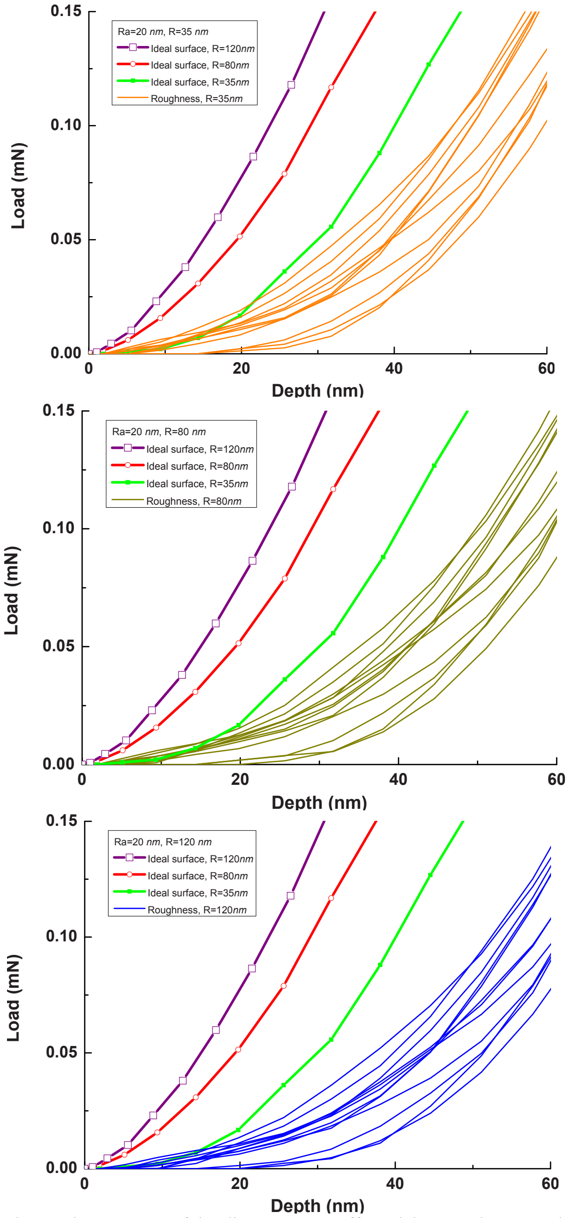

Fig.9. The scatters of loading process affected by roughness and indenter tip radius

5. Conclusions

The effects of surface roughness and indenter tip radius on nanoindentation measurement were simulated by developing a 3D FE roughness model loaded with Berkovich indenter. The 3D roughness surface was generated in Matlab and imported into Abaqus. Models with four roughness levels were built and simulated. The elastic-plastic behavior is affected by the surface roughness and a scatter of the Young's modulus and the hardness was observed. The levels of the scatter increase with the rise of roughness level. The mean values of the hardness are increasing with an increased roughness. However, the mean values of the Young's modulus is increasing for the roughness from 2 *nm* to 20 *nm*, and reversely deceasing for the roughness from 20 *nm* to 37 *nm*. The results from the simulations of combined effect of tip radius and roughness indicate that the sensitive of radius in roughness isn't so obvious in the scatter of load-depth curve, and there is also no significant effect on the hardness and the Young's modulus. Little effect of roughness was found in height of pile-up during the indentation deformation profile.

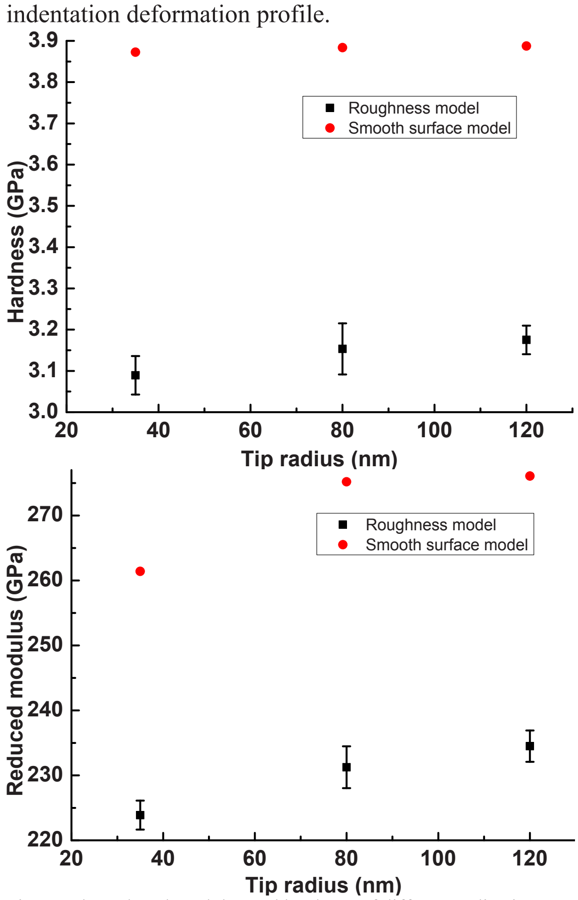

Fig.10. The reduced modulus and hardness of different radius in R_a = 20 *nm*

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