Investigation of Practical Hardness Information through Combined Systematic and Numerical Analyses

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Abstract

Indentation tests have been extensively used in assessing a material's hardness. In the current work, the minimum indent spacing, the minimum distance between the indent center and the edge of the specimen and the minimum thickness of the specimen were obtained by substantial mechanically instrumented indentation tests to quantify the factors that might influence the hardness measurement. Moreover, two-dimensional nonlinear FEA was performed to observe the size of the plastic zones lying underneath the indents and the interaction between them. In addition to the plastic zone study, the effect of the hardening modulus (strain hardening effect) was explored in these simulations. The simulations propose a separation distance between indents, based on the indent size, to avoid interaction between plastic zones. A change in the size of the plastic zone can be found, and quantified, as the hardening modulus is varied.

Introduction

Indentation tests are commonly used to measure mechanical properties of materials. For instance, mechanical properties of a thin film cannot be assessed by tensile testing which is extensively used in engineering to measure material's properties, but they can be measured by micro-indentation tests. Different indentation hardness tests standardized by indentation geometry, indentation size and other indentation parameters have been performed by different investigators. Indentation size effect of crystalline materials is studied in [1]. An analytical model for the size effect of flat punch indentation is developed by Campbell et al. [2]. Riccardi et al. demonstrate the fundamental indentation theory for flat-ended cylindrical punch [3]. In the current work, practical indentation hardness tests information is provided through extensive systematic experiments and numerical analyses. To be specific, the minimum indent spacing, the minimum distance between the indent center and the edge of the specimen and the minimum thickness of the specimen were assessed in this paper. To prevent interaction from neighboring indents, the criterion of minimum indent spacing is known as three times the lateral dimension of the indentation [4]. Phani et al. obtain the interindentation spacing using nano-indentations [5]. Simulations to predict the hardness of an AISI 4340 steel is presented in [6]. Indentation response affected by undulating multilayers is carried out by finite element models [7]. The simulation carried out in this work consider multiple parameters (applied load and hardening modulus) to illuminate the effect of plastic zones interaction beneath the indents on the hardness results. Details of this non-linear simulation will be elaborated more in the simulation section.

Experiments and Numerical Analyses

Systematic Experiments

To assess the minimum indent spacing and the minimum material thickness for indentation tests, mechanically instrumented indentation tests are performed.

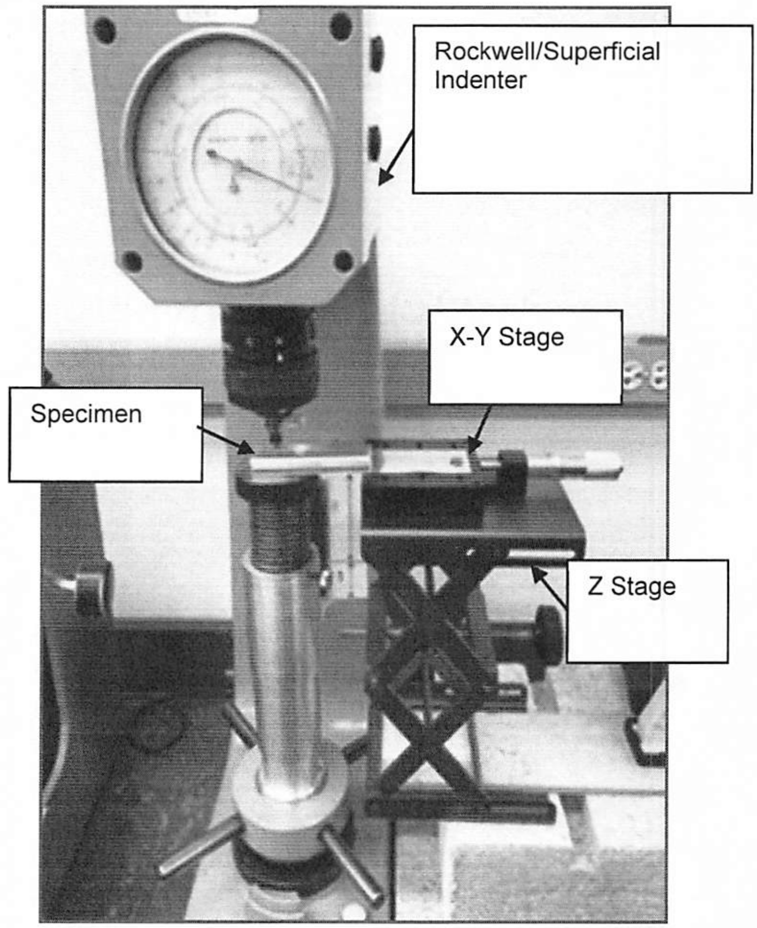


Figure 1. Instrumented Rockwell Indenter

The Rockwell test assesses the material hardness by measuring the indentation depth induced by a minor load and a major load from the tester. The position determined by the minor load is called zero position. After the application of the minor load, the major load is applied and removed, while the minor load is still in place. Then, the hardness value is displayed on a dial directly. One can also

use equation (1) to calculate the hardness value using the indentation depth [8]:
$HR = N - hs,$ (1)
where h is the indentation depth. N and s are scale factors.

As figure 1 shows, a Rockwell indenter, a X-Y stage, and a Z lift are applied in the experiments. The X-Y stage is used to move the specimen in the X-Y plane, while the Z-stage allows one to move the specimen along the z direction. The specimen utilized in the present study is 110 copper which has a yield strength of 255.1 MPa provided by the vendor [9]. Also, Rockwell F scale is recommended. For the indent spacing study, the following center-to-center spacings were used: 3, 2, 1.5 and 1 times the indent diameter. Some of the specimens are thinned down into different thicknesses to investigate the minimum thickness required in an indentation test to prevent any effect from the base.

Finite Element Analysis
2D non-linear finite element analysis is used to simulate the systematic indentation test as mentioned in the above section, which is carried out by ABAQUS. The current model simulates two indentations at pre-defined distance applied one after the other. A constant load 600N is applied in this simulation. As figure 2 shows, denser 4-noded bilinear plane strain elements are applied at the indentation area. (Mesh sensitivity analysis was performed.)

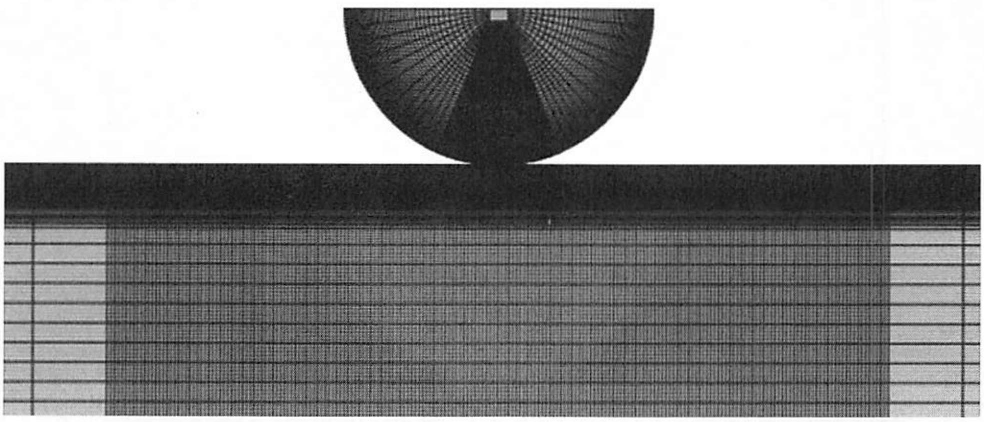


Figure 2. 2D FEA model

Mechanical properties of the substrate defined in this model are as following [10]:
Young's modulus (E): 130 GPa, Poisson's ratio (υ): 0.34, and hardening moduli: 1%, 5%, 10%, 15%, 20% and 25% of E. For the indenter, a semi-circle is chosen in this 2D simulation as the indenter for Rockwell F scale is a 1/16" ball. This indenter is defined as linear elastic with E:215 GPa, and υ: 0.28. In term of the boundary condition, the bottom of the substrate is constrained in the vertical direction while the left bottom corner is entirely fixed. The top surface of the substrate is free. The friction coefficient between the substrate and the indenter is 0.25.
The measurement of indentation hardness should be mentioned before wrapping up this section. Hardness (*H*) can be obtained by:
$H = F/A\,,$ (2)
where F is the applied indentation force in the vertical direction and A is the projected contact area.

Results and Discussion

Experimental Results

As figure 3 shows, the indentation hardness value tends to be higher with a smaller indent spacing. Also, the figure shows that the change in hardness results is not significant. More details of this study are presented in the simulation results section.

Indentation hardness results are expected to be significantly different as the specimen thickness decreases, which could be owing to either less resistance from the material or due to the strong response from the hard tester base. According to figure 4, the curve rises up, and then down with the decreasing specimen thickness. When the thickness decreases, the effect of the hard tester base on the results becomes significant. However, there is not much material left to resist the indentation if the material is too thin resulting in a decrease in hardness.

Hypothetically, hardness values are expected to go down owing to less material to resist localized plastic deformation if indentations are applied close to the specimen edge. The results shown in figure 5 are consistent with this hypothesis.

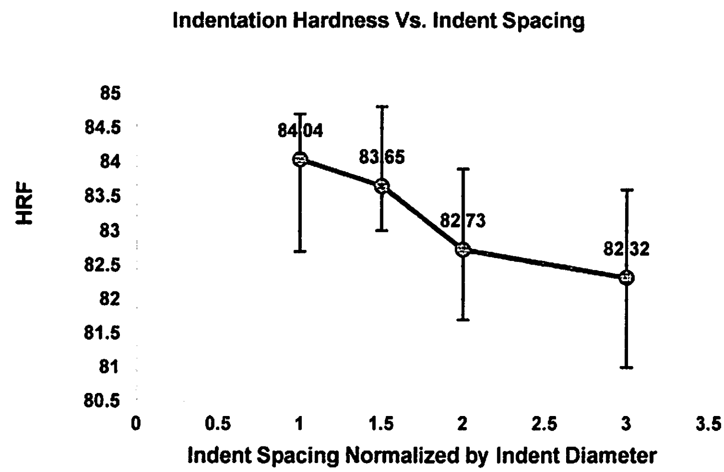


Figure 3. Indentation Hardness (from experiments) Vs. Indent Spacing for 0.375” thick specimen

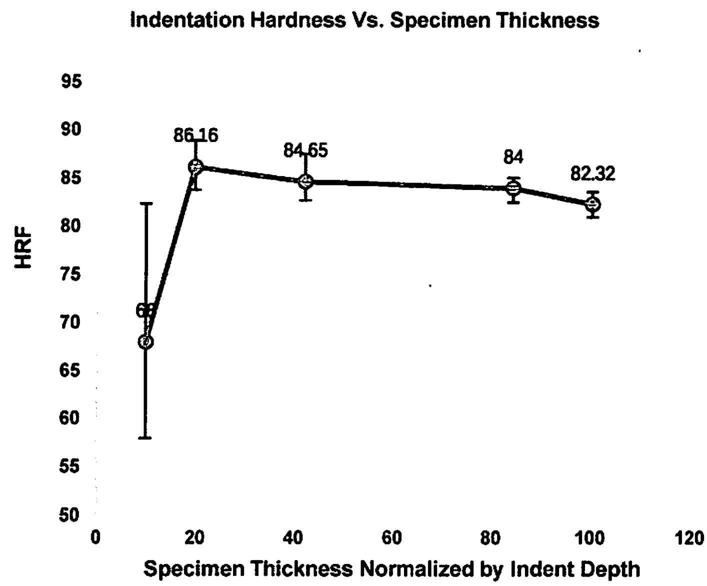


Figure 4. Indentation Hardness (from experiments) Vs. Specimen Thickness

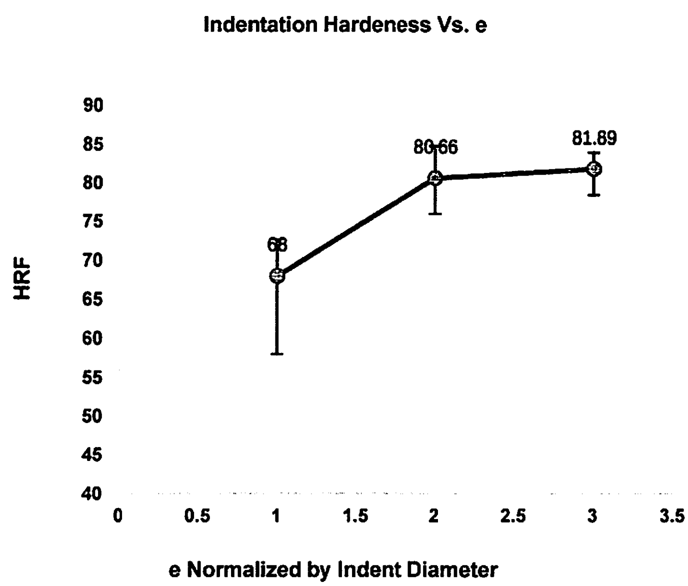
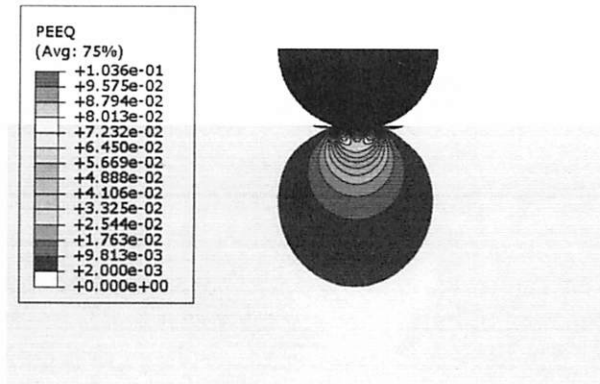


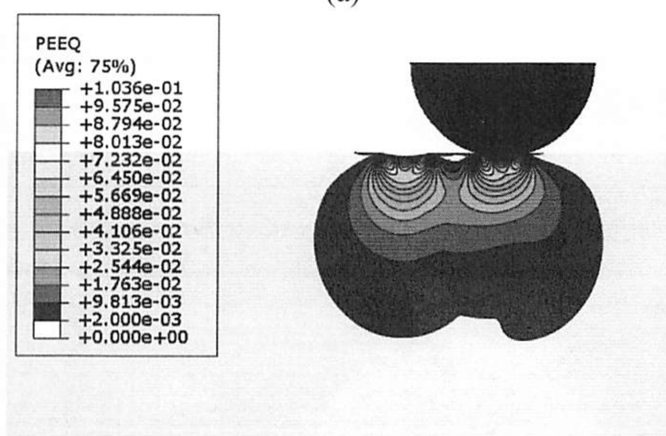
Figure 5. Indentation Hardness (from experiments) Vs. Normalized e (e is the distance from the indent center to the specimen edge) for 0.375" thick specimen

Simulation Results

In these simulation, two indentations at pre-defined distance are applied one after the other. Figure 6 (a) presents a simulation of one isolated indentation, which is followed by the second indentation spaced 2-indent-diameter away from the first indent as figure 6 (b) shows. According to figure 6 (b), the plastic zones of these two indents overlap. Subsequently, the hardness value of the second indentation is higher than that of the first indentation due to the strain hardening of the material induced by the first indentation. (Hardness values are provided in the caption for Figure 6.) Figure 7 shows consistency with the experimental results. The hardness value of the second indentation tends to increase as the indent spacing decreases due to the plastic zones interaction observed in figure 6. Also, the hardness value stabilizes at around 2-indent-diameter spacing.



(a)



(b)

Figure 6. Equivalent plastic strain (PEEQ) contours for 600N constant load, 5% hardening modulus for the strain hardening response of the material. (a) First indent (Hardness: 1463 MPa) (b) Second indent (at 2-indent-diameter spacing) (Hardness: 1519 MPa)

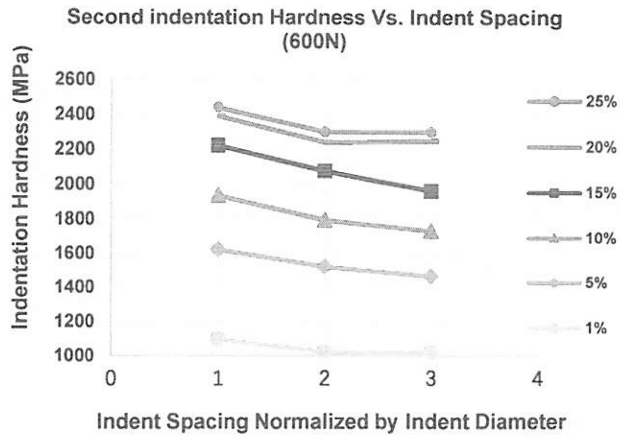


Figure 7. Simulation results (second indentation hardness vs. normalized indent spacing) for different hardening moduli (e.g., 1% means that the hardening modulus is 1% of E)

For an isolated indentation, the plastic zone under the indenter displays a quasi-circular shape (Figure 8). Measurements are taken for the lateral dimension of the zone (D1) and the longitudinal/depth dimension of the zone (D2). D1 and D2 are measured in units of 10^{-4}m. D1* and D2* in table 1 are normalized values, where D1 is normalized by the indent diameter, and D2 is normalized by the indent depth. H' is the hardening modulus. According to table 1, the plastic zone is smaller for the harder material. From the table, one better aim for a 4-indent-dimater indent spacing to prevent effect from either neighboring indents or specimen edge. Also, a minimum thickness of 40 indent-depths should be used in indentation tests to avert effect from the tester base.

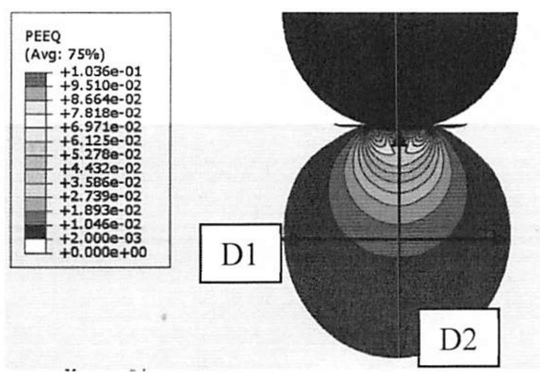


Figure 8. Plastic zone size beneath the indent

Table 1. Plastic zone dimensions for various hardening moduli (for 600 N)

H'	5%	10%	15%	20%	25%
D1 (units)	152.6	133.2	123.5	113.9	108.1
D2 (units)	156.4	137.3	127.7	118.0	108.2
D1*	3.7	3.8	4	4.3	4
D2*	37.2	41.6	44	45.3	45.4

Summary and Conclusions

In summary, extensive mechanically instrumented Rockwell indentation tests and 2D non-linear finite element analysis are performed in the current study. Hardness value tends to be higher with decreasing indentation spacing, owing to the plastic zones interaction beneath the indents, the effect of which is not significant unless the spacing between indentations is less than 2-indent-diameter. To prevent any effect from the neighboring indents and the specimen edge, the optimal indent spacing should be 4-indent-diameter. Moreover, a minimum thickness of 40-indent-depth should be used in indentation tests to avert any effect from the tester base.

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