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Analysis of Indentation Test Using Solid Works Simulation

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Abstract: The finite element analysis of spherical indentation was conducted using the SolidWorks simulation software. The relationship between the load and indention was determined, and comparison with the Hertzian solution was made. In this study, spherical indenters of diameter 5, 10 and 15 mm were used to assess the effect of indenter radius on indentation response at a specified load. The outcome of our study shows that the resulting load-indentation response does not closely correlate; as a result, a difference of 21.2% was observed between the hertz solution and simulated results. The increase in diameter was observed to be associated with the corresponding decrease in indentation depth and the indentation stress. The von Mises stress contour at maximum load was analysed and was observed to be the highest on the indented surface beneath the indenter. The resultant displacement contour shows a uniform displacement distribution.

Keywords: Finite element analysis, hertz solution, spherical indentation

1. Introduction

The rapid development in the advancement of engineering materials and their success in applications at different industrial sectors necessitated the increase in demands for a practical assessment of their mechanical properties. Indentation testing, which is one of the advanced techniques in the characterisation of mechanical properties of engineering material, has been widely adopted due to its cost-effectiveness, convenience and non-destructive method for solving such problems. The success of material is dependent on their Mechanical characterisation; thus; the area of indentation has gained popularity among methods for characterising the properties of materials. The determination of the properties of a material using the indentation method has been given more consideration in recent time. Consequently, it has been used in the measurement of depth penetrated by an indenter into a test specimen with the load applied—this tests method which has been applied mainly to obtain and interpret hardness. Besides, it can also be used for providing information about the mechanical properties of a material and deformation behaviour [1].

The process involves pushing an indenter of known shape (sphere) made of a very hard material such as diamond into the surface of a test material to a certain depth, while monitoring and recording the load-displacement responses. Mechanical characteristics of the test samples are then extracted from the load-displacement curves using well-established equations based on elastic contact theory or based on the Finite Element Method.

Indentation has been successfully used to measure the properties of materials as this technique allows the characterisation of mechanical responses of a smaller sample of materials over a more comprehensive range of resolution and deformation magnitude through the choice of size and geometry of indenters and the indentation depth.

Where the application of a tensile test becomes difficult, the spherical indentation test has been useful. The analysis of results obtained from such a test is complicated because of the complex triaxle state of stress on the

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spherical indenter. However, such types of challenges have been significantly overcome by continuous indentation measurements and most significantly by the application of finite element analyses [2].

Regardless of the simplicity of the indentation testing, it provides different information on a material, but this information tends to differ from those gotten through the traditional testing methods; thus, it becomes difficult to extract specific material information from material test results independently. Following such challenges, indentation tests have become unsuitable in the measurement of different material properties; as a result, the test is used merely for measuring hardness and elastic modulus. However, the advent of finite element analysis and the improvements of the continuous measurement techniques, this barrier is being removed. [2].

Numerical simulations which are based on finite element analysis have provided the opportunity for the development of realistic constitutive models, and the acquisition of essential material parameters through the matching of simulated indentation responses with force-displacement data acquired from physical experiments. Numerical indentation studies are typical for the determination of elastic modulus, hardness value, as well as yield point and strain hardening exponent in plastic materials [3].

The applicability of computers and numerical techniques has led to the fast development of various indentation testing methods in recent times which includes spherical indentation as applied by[4]–[7]. Computational and theoretical studies have simultaneously emerged intending to clarify the contact system and deformation mechanisms. These processes have led to the extraction of material's properties systematically from the load-displacement curves gotten from an indentation process[8].

The application of indentation analyse has developed into a standard method for the analysis of mechanical properties of engineering materials, and the application of finite element analysis simulation has given further insight to the experiment for better understanding and clearer description of material properties[9]. In recent time the numerical methods have become prominent and mostly preferred over conventional methods due to its ability to treat complex situations mostly occasioned by nonlinear situations. Various Finite element analysis software such as SIMULIA ABAQUS, ANSYS, MSC-NASTRAN LS-DYNA, and COMSOL have been used for the analysis of such indentation test. Thus, there is a need to conduct such analysis with SolidWorks simulation which also have a similar capability. Thus, this study aims at analysing indentation test using the SolidWorks simulation package and compare with the hertz solution.

v_i	Indenter Poisson's Ratio
P	Indentation load
E_i	Indenter Modulus
E_m	Material Modulus
E_r	Reduced or effective modulus
a	Contact radius,
R_e	Combined radius of the indenter and test material
h	maximum indentation depth
R_m	radius of the test material
R_i	radius of the indenter
A_proj	projected area

2. Theoretical background and application of common indenters

The commonly used materials for indenter are presented in table 1. These indenters have been widely applied for indentation on various kind of materials, ranging from brittle, ceramics to ductile metals [10]–[12].

Table 1 - Commonly used materials for indenter

Material	Elastic modulus (*GPa*)	Poisson's ratio	Hardness (*GPa*)
Diamond	1147	0.07	100 above
Tungsten	441	0.28	6.6
Sapphire	370	0.25	30
Fused silica	72.1	0.17	8.8

In an indentation testing, the determination of the projected area of contact of the indenter which is known to be a function of the indentation depth is a critical factor for the extraction of elastic modulus and hardness value of any material. Figure 1 depicts a perfect geometry of the contact area of different indenters which penetrates a test material to a depth h.

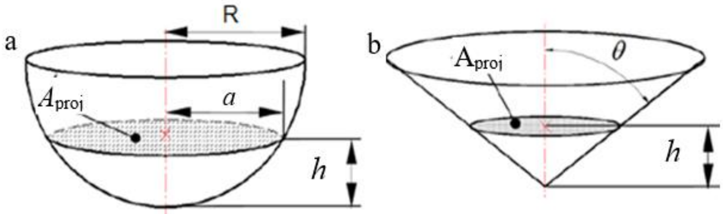


Fig. 1 - Geometrical representation of classical indenters(a) spherical indenter; (b) conical indenter [13]

2.1 Contact between spherical body and an elastic half-space

The study of spherical indentation on a flat surface by Hertz is illustrated in figure 2. The study shows that the relationship between indentation load, contact radius, reduced modulus and combined radius of the indenter and test material is given by equation (1) below. The combined radius and the maximum indentation depth h are also given by equation (2) and (3) respectively.

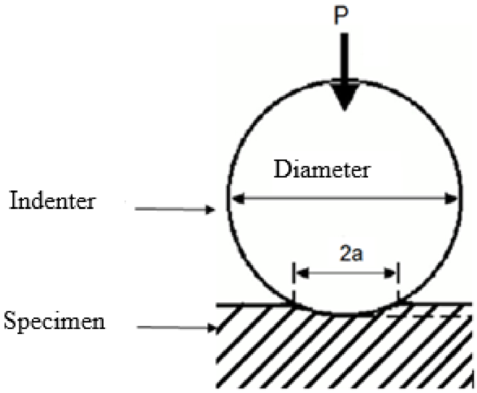


Fig. 2 - Loaded spherical indenters on a flat surface [14]

$$a^3 = \frac{3R_e P}{4E_r} \quad (1)$$

$$\frac{1}{R_e} = \frac{1}{Ri} + \frac{1}{R_m} \quad (2)$$

$$h = \frac{3P}{4aE_r} \quad (3)$$

For a spherical indenter on flat test material, the radius of the test material tends to infinity which makes it inconsequential in the analysis, thus making $R_e = R_i$ in equation (2) above. The total compression between the two bodies, and the indentation load is given by equation (4) and (5) respectively.

$$h = \frac{a^2}{R_e} \quad (4)$$

$$P = \frac{4}{3} E_r \sqrt{R_e}\, h^{1.5} \quad (5)$$

3. Methodology

3.1 Modelling

3.1.1 SolidWorks Simulation Software Package

SolidWorks simulation is integrated with CAD software for creating and editing model geometry. It is a solid parametric, feature-driven CAD system developed especially for Windows operating systems. It is a package of engineering simulation programs based on the FEM capable of performing linear and nonlinear simulations [15]. The SolidWorks simulation package was used in different stages of this study from the 3-D model parts creation, creating the assembly of the indenter model with the test material model, setting up the contact Interaction, meshing and the extraction of results.

3.1.2 CAD modelling

The finite element model and simulation of the spherical indentation test in this study was carried out using the SolidWorks 2014 education version. The analysis model initially consists of spherical indenters having radius 2.5 mm, 5 mm and 7.5 mm respectively. The test specimen was modelled as a cylindrical part with the height and radius of 20mm and 60mm, respectively as shown in figure 3.

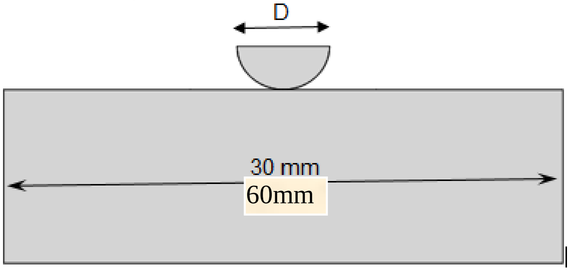


Fig. 3 - 2D view redraw of the indentation assembly

The indenter and the test material were produced by extruding the 2-D sketch from SolidWorks parts environment. The revolve tool was used to produce the indenter from a quarter circle sketch. The 3D indenter and test material were assembled in the SolidWorks assembly environment as shown in Figure 4.

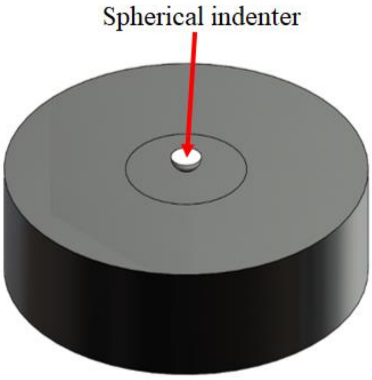


Fig. 4 - 3D general CAD redraw demonstrating the FEM analysis

3.2 Simulation

3.2.1 Nonlinear analysis in SolidWorks simulation

Nonlinearity is generally known to arise due to nonlinear materials on nonlinear geometry. As the process of indentation test generates deformations on the test material, the magnitude of this deformations affects the system structure responds due to the different geometry, which leads to the nonlinearity of geometry. Consequently, the nonlinear analysis has been adopted in this study. The force control option was used in the simulation. This option allows the increment of loading by auto stepping, thereby evaluating the responses at every solution step. This option is also used by default due to its efficiency in most practical cases.

3.2.2 Property of Analysis of the Material

Although the application of rigid indenter to different indentation tests has been used, other studies have also shown that spherical indenter cannot be completely modelled as a rigid component. The limitation is because the deformation of the indenter has a contributing effect on the indentation depth, size and shape. Karthik et al.[16] have successfully applied the non-rigid spherical indenter in finite element simulation, and thus similar approach was adopted in this study. The material characteristics selected for analysis are similar to those found in kucharsky and Mroz [17] and are described in Table 2. The material was modelled as isotropic material. The reduced or effective modulus of the system, which is 83604 MPa is obtained by equation (6).

Table 2 - Material property inputs for the analysis

Part	**Material**	**Elastic modulus (*GPa*)**	**Poisson's ratio**
Indenter	Diamond	1141	0.07
Test material	Aluminum alloy	74.5	0.33

$$E_r = \left[\frac{1-\nu^2}{E_m} + \frac{1-\nu_i^2}{E_i}\right]^{-1} \tag{6}$$

3.2.3 FEA Model and Boundary Conditions

Since models were symmetrical, a quarter of the design was used for the study as shown in Figure 5. The framework was subsequently imposed the necessary boundary conditions.

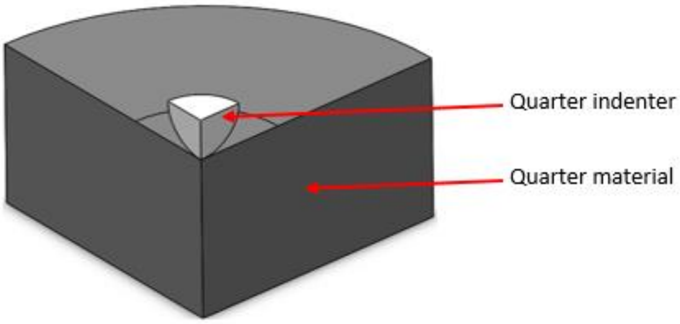


Fig. 5 - Redraw of 3D Finite element analysis model

The analysis was carried out in the simulation environment of the SolidWorks using the nonlinear analysis and was based on the symmetric assumption. This assumption includes the horizontal direction restrictions of the movement of the indenter and the material on the vertical axis at the symmetry line. The Boundary conditions were similar to those used in an axisymmetric FEA study on spherical indentation conducted by Gandhi et al [18]. The boundary conditions were set in such a way as to restrict the nodes translation in a specified manner. The radial degree of freedom of the indenter and test material were constrained along the axis of symmetry. The bottom surface of the specimen material was fixed in order to prevent any axial or radial displacements of the specimen. Movement of the indenter in the *y*-direction was given a fixed negative value of 3 mm.

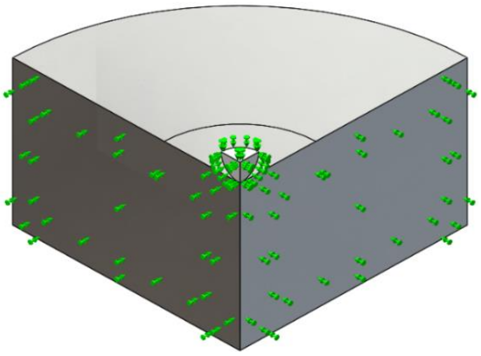
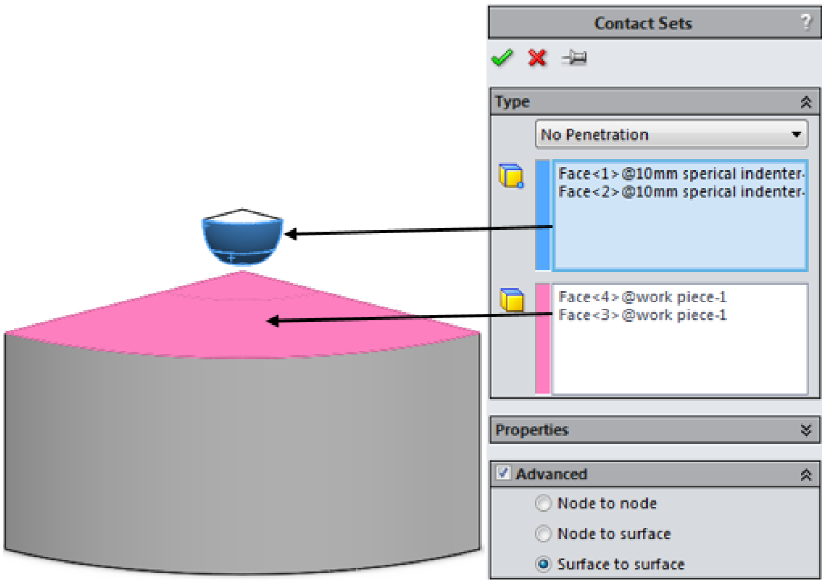


Fig. 6 - 3D redraw of analysis model showing fixtures and boundary conditions represented in green colours

3.2.4 Contact Settings

Contact behaviour between the parts was defined from the simulations contact set menu, the indenter and the test material were modelled as a contact pair. The indenter surface was defined as the 'source' while the top of the specimen was the 'target' surface, as shown in Figure 7.



No Penetration

Face<1>@10mm sperical indenter-
Face<2>@10mm sperical indenter-

Face<4>@work piece-1
Face<3>@work piece-1

☑ Advanced
○ Node to node
○ Node to surface
● Surface to surface

Fig. 7 - Contact between the indenter and specimen

The interaction between the contacting surfaces is also a characterize of the friction behaviour between the surfaces. Nevertheless, in this study, the friction effect was neglected in all the models assuming that there is no slip between the contacting surfaces. Due to the geometry of the contacting surfaces, the surface to surface contact set was applied because it allows only faces to interact, and it increases accuracy.

3.2.5 Mesh generation and mesh sensitivity test

The model initially meshed with a draft quality mesh with an element size of 4.84 mm for the whole system, and initial analysis was conducted based on the draft quality mesh settings. This meshing was done in order to have a rough estimate of the expected results. In order to study the effect of mesh sizes on the accuracy of results and to determine the most effective mesh, further mesh test was conducted while maintaining previous boundary conditions. Four analysis was conducted with four different mesh sizes respectively using the tetrahedral element, the details are presented in table 3. The outputs were used to check for convergence and to ascertain the most effective mesh for higher accuracy of results because a single analysis to an FEA provides only a snapshot of what a possible result might be.[19]. One primary reason for performing multiple analyses is to determine whether or not a study converges to an acceptable solution.

Table 3 - Mesh test parameters

Mesh used	Element size	Total element
Draft quality	4.8	1149
Standard	2.42	7023
Standard	1.95	12942
Standard	1.50	25869
Standard	1.30	38809
Standard	1.05	67288
Standard	0.95	88983
Standard	0.92	98156
Standard	0.86	115686
controlled mesh	4.838/1.2	1831

In order to reduce the computation time, Controlled meshing was also applied. Thus, the element sizes which are far away from the contact zone are made coarser than those at the contact zone as shown in figure 8.

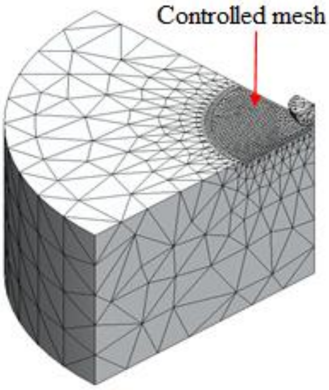


Fig. 8 - Finite element model showing controlled mesh

3.3 Analysis Procedure

Series of indentation simulation tests were performed with the spherical indenters of 5 mm, 10 mm, 15 mm and 20 mm diameters on the surface of the test specimen. The model was constrained to force the indenter progressively onto the material's surface to the pre-set indentation depth and series of indentation simulations were performed for each case. The reaction force which represents the summation of the forces over the contact area along the indentation direction, and the corresponding indentation depth (load-displacement) were extracted from the simulation-time response plots. The results obtained were from the loading cycle.

4. Results and discussion

4.1 Force-displacement responses

The load-indentation curve obtained from the SolidWorks simulation and the Hertz solution for 5mm spherical indenter are compared in Figure 9. At 42kN of load, the indentation depth obtained from the simulation and those obtained by Hertzian solution are also shown in Figure 9.

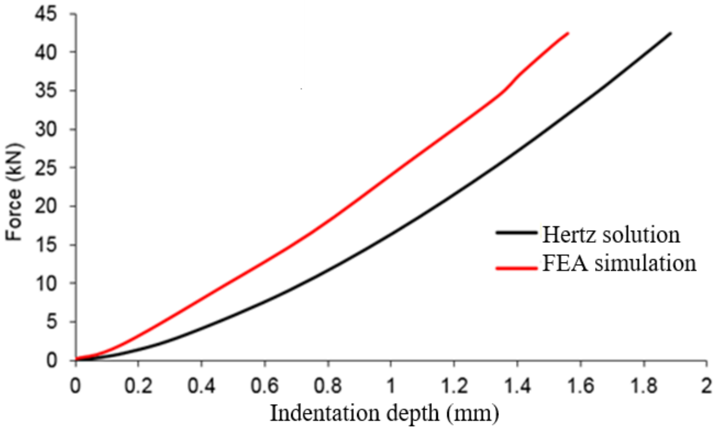


Fig. 9 - Comparison of Hertz solution with Finite element simulation using 5mm indenter

The curves exhibit the same pattern but differ in indentation depth by 21.2% at the same maximum indentation load. It can be seen that the curves correlate and fits better from the small load and deformation point but diverges widely as the load increases. This trend indicates that the hertz solution is more suitable for smaller deformations which conforms with the assumption of Hertzian Theory of Elastic Deformation. The difference between the SolidWorks simulation result and the Hertzian solution could also be because the hertz solution considers ideal case which considers only the vertical forces. The solution, therefore, the Hertzian solution may not be suitable for testing of materials with large deformation, and this has become a limitation associated with the hertz solution. It also reveals that the Hertz solution does not provide the same solution as the simulated results achieved with SolidWorks this is because Hertzian theory assumes ideal situation of frictionless contact which may not be realistic.

4.2 Mesh sensitivity analysis

The plots obtained from the mesh test are given in Figure 10. The graph shows displacement versus the corresponding number of elements. It could be observed from the figure that as the number of elements increases (as the element size gets smaller) the curve levels off approaching a limiting value, which indicates a convergence of the solution. The graph indicates that the stiffness of the material decreases with smaller element size but becomes constant from a particular point regardless of the reduction in element size, indicating attainment of acceptable accuracy of the result. Although the smallest element size achieved the most accurate results, mesh control was also applied locally to specific areas of interest (contact). With the mesh control approach, similar accurate results were achieved at a considerably lesser computational time. This reduction in the analysis run time was as a result of lesser number of equations due to lesser number of elements. The mesh-controlled study with fewer elements than the most refined, high-quality standard mesh are capable of giving reasonably accurate result at lesser computation time.

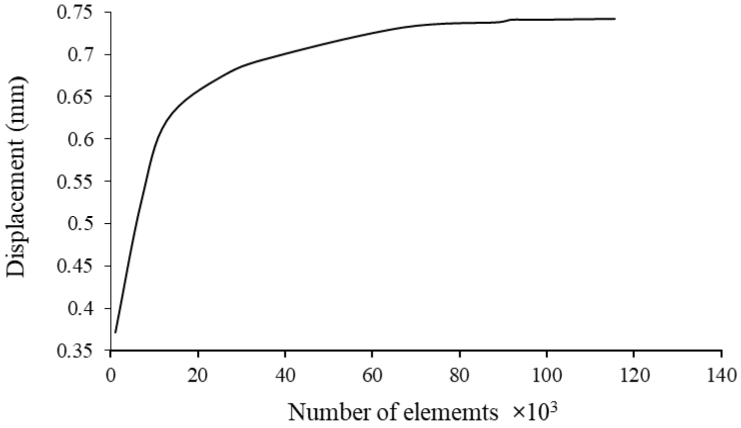


Fig. 10 - Mesh convergence test based on the displacement

4.3 Indenter size effect

The responses obtained using various indenter size under the same maximum load are given in Figure 11. It can be seen that more depth was achieved with indenter of 5 mm compared to 10 mm and 15 mm indenter at the same maximum load.

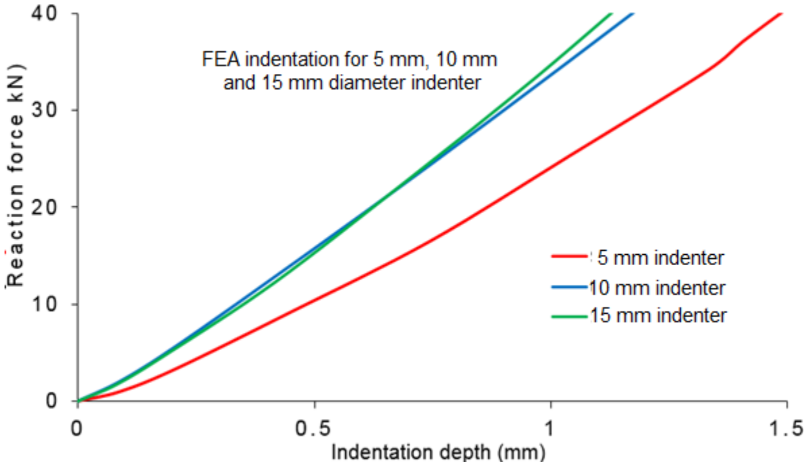


Fig. 11 - Comparison of Indenter size under the same maximum load

The 5mm indenter has a 31.6% depth higher than the 15 mm indenter, while the 10 mm indenter shows a close correlation of 98.2% with the 15 mm indenter. This phenomenon can be attributed to the change in the contact area. The observed behaviour implies that the increase in contact area requires a corresponding increase in the indentation load in order to achieve the same indentation depth with increasing indenter radius. Consequently, this indicates that indenters of smaller radius are more effective and require lesser load to achieve higher indentation depth and accuracy of analysis due to their smaller contact area. As it is known that force is proportional to compression, thus, the reduction in the area will lead to increased pressure on the test material surface which has accounted for the higher indentation depth for indenter of 5 mm radius as compared to the 10mm and 15 mm indentation depths.

Further analysis also showed that under the same load, a stage is reached where increasing the indenter radius does not cause any further increase in indentation depth, as shown in Figure 12.

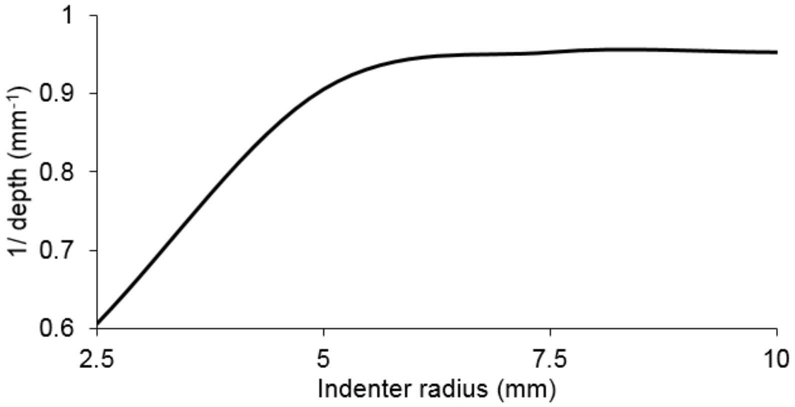


Fig. 12 - Effect of indenter size on indentation depth

This result implies that at a specific maximum indentation load, there is a corresponding maximum indenter radius that is effective for conducting indentation test. The knowledge of the effective dimension will be of great advantage in spherical indentation analysis as it will make the analysis cheaper and faster.

5. Conclusions

The analysis of spherical indentation test has been numerically simulated using the Finite element analysis, using the SolidWorks simulation software. The simulated indentation result was compared with those obtained by the hertz solution. The effect of indenter radius was also analysed.

The simulated indentation depth was inconsistent with that of the hertz solution as the depth obtained by the hertz solution was higher than the simulated by 21.2% at the specified load but shows little agreement at the initiation of loading. Thus, the hertz solution is limited and cannot be entirely relied upon for numerical analysis of indentation because it was noticed to correlate only for minimal displacements. The load and displacement relationship show an elastic deformation of the material. The radius of indenter was found to determine the accuracy and efficiency of analysis because a larger radius was associated with larger load requirement; thus, the smallest possible indenter is more efficient and effective for analysis.

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