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Home > Applied Mechanics and Materials > Editorial board

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Share: 135
Main Theme: Advances in Applied Mechanics and Materials

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Paper Titles published in this Main Theme:

- **Sol-Gel Synthesis of Zn Doped HA Powders and their Conversion to Porous Bodies**
  Authors: Abreeq Naqshbandi, Is Sooyan, Gunawan, Suryanto
  Chapter 4: Material Science and Engineering
  Abstract: The present study was aimed at fabricating porous ceramic scaffolds via polymeric sponge method for biomedical applications using as...
  Page 603

- **Synthesis and Characterization of Zinc Oxide Nanoparticles via Self-Combustion Technique**
  Authors: Poppy Puspitasari, Andoko, Eddy Sutadji
  Chapter 4: Material Science and Engineering
  Abstract: Zinc oxide (ZnO) is a unique material which has been used in many researches. However synthesizing nanosize ZnO remains a challenge. This...
  Page 609

- **Effect of Ingredients on Flexural Strength of Friction Composite**
  Authors: Jamasi, Viktor Malau, Mohammad Noor Ilman, Eko Surojo
  Chapter 4: Material Science and Engineering
  Abstract: In the present work, a friction composite material which will be used for material of train brake shoe was investigated to study the effect...
  Page 615

- **Dielectric Properties for the Ring Opening Polymerization of e-Caprolactone**
  Authors: Mohd Johari Kamaruddin, Muhammad Abbas Ahmad Zaini, Anwar Johari, Tuan Amran Tuan Abdullah
  Chapter 4: Material Science and Engineering
  Abstract: A dielectric property study was performed across a wide range of frequencies and temperatures on ring opening polymerization of...
  Page 621

- **P-h Curves and Hardness Value Prediction for Spherical Indentation Based on the Representative Stress Approach**
  Authors: I Nyoman Budiarsa, Mikkad Jamal
  Chapter 4: Material Science and Engineering
  Abstract: In this work, finite element (FE) model of spherical indentation has been developed and validated. The relationships between constitutive...
  Page 628

- **Simple Recipe to Synthesize BaTiO$_3$-BaFe$_{12}$O$_{19}$ Nanocomposite Bulk System with High Magnetization**
  Authors: Dwita Suastiyanti, Soegjlono Bambang, M. Hikam
  Chapter 4: Material Science and Engineering
  Abstract: Barium titanate BaTiO$_3$ (BTO) - barium hexaferrite BaFe$_{12}$O$_{19}$ (BHF) nanocomposite could be as a raw material...
  Page 634

- **Effect of Cellulose Acetate Phthalate (CAP) on Characteristics and Morphology of Polysulfone/Cellulose Acetate Phthalate (PS/CAP) Blend Membranes**
  Authors: Asmadi Ali, Rosid Mohd Yunus, Mohamed Awang, Anwar Johari, Ramli Mat
  Chapter 4: Material Science and Engineering
  Abstract: Polysulfone (PSF) membrane is categorized as hydrophobic membrane that easily fouled during membrane operation process. The presence of...
  Page 640
Analysis of Fiber Glass/Vinyl Ester Composite Subjected to Internal Pressure Loading for Compressed Natural Gas (CNG) Tube Type IV Application

Authors: Hosta Ardhyananta, Risa Nurin Baiti, Martha Adi Afrianto, Dendi Kurniawan

Chapter 4: Material Science and Engineering
Abstract: Natural gas in the form of compressed natural gas (CNG) has a pressure of 20 MPa. Glass fiber/vinyl ester composite has potential to be...

Microstructure Study on Fe/Cr Based Alloys Added with Yttrium Oxide (Y2O3) Prepared via Ultrasonic Technique for Solid Oxide Fuel Cell (SOFC) Application

Authors: Dafit Feriyanto, Maizlinca Izwana Idris, Darwin Sebayang, Ashraf Bin Othman, Pudji Untoro

Chapter 4: Material Science and Engineering
Abstract: Solid oxide fuel cells (SOFC) are the current research having several potential to obtain high efficiency, high energy–density power...

Microstructure and Magnetic Properties of Barium Hexaferrite Produced by Sol Gel Auto Combustion for Radar Absorber Material (RAM) Application

Authors: Widyaastuti, Endah Kharismawati, M. Zainuri, Hosta Ardhyananta

Chapter 4: Material Science and Engineering
Abstract: Barium hexaferrite (BaFe12O19) with hexagonal structure has been known as the high performance magnetic for Radar...

Showing 101 to 110 of 131 Paper Tides
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P-h Curves and Hardness Value Prediction for Spherical Indentation Based on the Representative Stress Approach

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\textbf{Keywords:} Spherical Indentation, Rockwell Hardness value, Representative stress, P-h curve.

\textbf{Abstract.} In this work, finite element (FE) model of spherical indentation has been developed and validated. The relationships between constitutive materials parameters ($\sigma_y$ and $n$) of elastic-plastic materials, indentation P-h curves and hardness on spherical indenters has been systematically investigated by combining representative stress analysis and FE modelling using steel as a typical model material group. Parametric FE models of spherical indentation have been developed. Two new approaches to characterise the P-h curves of spherical indentation have been developed and evaluated. Both approaches were proven to be adequate and effective in predicting indentation P-h curves. The concept and methodology developed is to be used to predict Rockwell hardness value of materials through direct analysis and validated with experimental data on selected sample of steels. The Hardness predicted are compared with the experimental data and showed a good agreement. The approaches established was successfully used to produce hardness values of a wide range of material properties, which is then used to establish the relationship between the hardness values with representative stress.

\textbf{Introduction}

Indentation test is an important materials testing method in which a sharp or blunt indenter is pressed into the surface of a material. [1]. One significant advantage of indentation is that it only requires a small amount of materials, this makes it very attractive for the characterisation of materials with gradient property where standard specimen is not readily available such as \textit{in situ} or \textit{in vivo} tests [2] However despite its wide use, the materials behaviour (represented by the hardness or P-h curves) are not explicitly linked with the constitutive material properties. Further work is required to be able to predict indentation resistance (P-h Curves and/or hardness) from constitutive materials parameters. One of the most effective ways to analyse the indentation process has been the representative method [3]. Earlier works showed that hardness can be related to the stress of the indented material, $\sigma_y$, corresponding to a representative strain, $\varepsilon_p$, which represents the mean plastic strain after yielding. The concept coupled with finite element (FE) modelling has been used successfully in analysing sharp indenters where the representative strain and stress is well defined with a fixed indenter angle [4]. It is of great importance to extend this to spherical indentation and associated hardness system. One particular case is the Rockwell B test, where the hardens is determined by two points on the P-h curve of a spherical indenter. In this case, an established link between materials parameters and P-h curves can naturally lead to direct hardness estimation from the materials parameters (such as yield stress and work hardening coefficients). This could provide an useful tool for both research and practical applications.

\textbf{Materials and Experimental}

The material used were steel. The tensile tests were performed using a material testing machine with extensometer. Sample steel used is solid rod-shaped elliptical of 5 mm in diameter and 90 mm long has a holder on the edges. The two main materials were used in this experiment include a carbon steel (0.1\% C Steel) and mild steel specimen, The samples were sectioned, mounted in resin
before being polished with diamond paste. The Rockwell hardness test was performed using: Wilson Rockwell hardness tester (ACCO Wilson instrument division, USA). The indentation using spherical indenter B scale, with \( R = 0.79 \) mm (Diameter steel ball =1/16 in). These HRB hardness data be used to validate the representative stress based hardness evaluation and property prediction program to be developed.

**Results And Discussions**

Axial symmetric 2-D space FE models were constructed to simulate the indentation response of elastic plastic solids using the commercial FE code ABAQUS, are shown in Figure 1(a). Model was used due to the symmetry of the spherical indenter. In the model, the sample size can be changed to ensure that the sample is much larger than the indenter radius/contact area during the indentation to avoid potential sample size and boundary effects [3]. The bottom line of the model was fixed in all degree of freedoms (DOF) and the central line was symmetrically constrained. The model used a free mesh controlling only the key areas, this allow implementing the mesh size in the parametric file. A gradient meshing scheme has been developed for different regions. The simulation performed used \( R = 0.79 \) mm, and specimen model used young’s modulus= 200 GPa. Poisson ratio= 0.2. The mesh size is 10\( \mu \)m in the region underneath and around the indenter, while the mesh of other regions used single bias to obtain gradient mesh tightly into underneath and around the indenter to improve the accuracy of the model. In FE modelling, the accuracy of results is influenced by many factor such as the mesh shape and density, element type, friction condition and the boundary conditions [5]. In this work encompassing a domain of Yielding strength \( \sigma_y \) from 100 to 900 MPa and strain hardening exponent \( n \) varying from 0.0 to 0.3 and Poisson’s ratio \( \nu \) was fixed at 0.2.

![Figure 1(a)](image1.png)

**Figure 1(a)**. FE Model of the spherical indentation test and close the mesh underneath. Figure 1(b).Typical force indentation depth (P-h) curves during loading and unloading for the spherical indentation with different indenter size (materials properties used \( \sigma_y = 350 \) MPa, \( n = 0.2 \))

![Figure 1(b)](image2.png)

The results of simulations FE model Spherical establish will produce p-h curve (Force-Indentation depth). Figure 1(b) shows typical P-h curve during loading and unloading phase of a typical elastic-plastic materials with different indenter sizes. The loading curve represents the resistance of material to indenter penetration, while difference between the loading and unloading curve represents the energy loss [6]. With increasing indenter size, the trends of the loading curves are similar among these models, the force value at comparable indentation depth is much higher with larger indenter sizes. The Spherical FE Model developed were validation with analytical solution of elastic material base of relationship using a known analytical solution [3] for indentation of linier elastic materials.
Where \( F_z \) is the reaction force, \( R \) is the indenter radius; \( E \) and \( v \) is the Young’s modulus and Poisson’s ratio of material, respectively. \( \delta \) is the indentation depth. As shown in the Figure 2 visible the trend analysis in accordance with the numerical force–displacement data simulation FE Model and resulting using the following analytical. This indicates a statistically curve fitting the data equally well and the FE model is congruous with the analytical model. The correlation coefficients between these two curves using a least square regression method is within 99.9%.

\[
F_z = \left( \frac{16R}{9} \right)^\frac{1}{2} \cdot \frac{E}{1-v^2} \cdot \delta^2
\]

Figure 2 Comparison between the FE numerical force–displacement data and analytical solution with elastic material model. (a) R=0.5mm; (b) R=0.79 mm; (c) R=1.25mm.

The FE spherical model was further validated by comparing the P-h curve with an elastic-plastic material model and published result data [7]. In the FE model, the material properties used were depicted directly from the published work. As shown in Figure 3 the numerical results showed good agreement with the experimental data, which suggests that the FE model is valid and the results are accurate.

The results of simulations with FE model Spherical establish will produce p-h curve. After evaluation of several approaches, two approaches have been found to be effective in representing the curves with adequate and acceptable accuracy. The first method is to use second order polynomial fitting in the form of \( P= C_1 h^2+C_2 h \). The second fitting approach to be explored to represent the curve is using the force at different indentation depths. If the correlation between the force at different depth and the constitutive material properties and/or the representative stress is established, then the full P-h curve can be determined. For spherical indenter, the angle changes with the increasing depth, no fixed representative strain is readily available.

Figure 3. Comparison of numerical results with published experimental data [7] of indentation with a spherical indenter (R=1.25 mm) showing the validation of FE model with elastic-plastic materials.
However in general, based on the deformation mechanism of an indentation process, the material
deformation is controlled by the elastic deformation and the yielding, so we propose to use an
effective representative stress which potentially could be linked to the C1 and C2 parameters, thus
representing the full P-h curve. In the equation, C2 is linear term in the equation, so the fitting was
conducted directly associating C2 to E/σr, this term represents the balance of elastic and plastic
properties. Figure 4(a) plots the C2 vs. E/σr, with the best representative strain for C2. It clearly
shows that there is a reasonable correlation between these C2 and E/σr, and the fitting is influenced
by the representative strain used. At a representative strain of 0.01, the fitting is reasonable with the
best correlation coefficient.

\[ C_2 = 3566.9 \left( \frac{E}{\sigma_r} \right)^{0.855} \]  

(2)

The relationship directly between C1 and E/σr, has been explored with different representative
strains. Figure 4(b) The fitting are much better than that for fitting between C1/σr vs E/σr. Comparing the correlation with different representative strains, the most effective reference strain is
0.07, which give an equation of:

\[ C_1 = 3606.8 \left( \frac{E}{\sigma_r} \right)^{-1.252} \]  

(3)

The correlation coefficients is over 93%. Further increasing or decreasing of the representative
strains shows no improvement in correlation of the fitting. So this is the value in predicting the P-h
curves to evaluate its accurate. The depth approach is much straight forward physically. In this case,
the force at an indentation depth with different material properties were formulated then the
relationship between the force and the representative stress was explored. An optimum
representative strain and equation was determined for each depth. Figure 4(c) shows the force data
at different depth plotted against E/σr. The data for each depth was based on evaluation of series
representative strain values similar to the process used for the Cv, C1 and C2. The optimum strain at
h0.01 is 0.05, h0.02 is 0.01, h0.05 is 0.033, h0.075 is 0.02 and h0.1 is 0.045. These equations for
each depth can then be used to predict the point on the P-h curves.

The concept and methodology developed is to be use to predict hardness value (HRB) of material
trough direct analysis and validated with experimental data on selected sample of steel. The
Rockwell hardness is predicted directly base on P-h curve predicting using the representative stress
equation established. Figure 5 shows the P-h curves of the two steel samples from direct FE
modelling (using the stress strain curves as input material properties) and the P-h curves predicted
using equations (2)-(3). Figure 5(b) plots the HRB values calculated based on the data in Figure
5(a) in comparison with the experimental results. In all cases, the prediction based on the
representative approach (equations 2-3) showed a good agreement with the test data and the FE
data. Works has been conducted on other materials, and the prediction results showed a similar
degree of agreement. This suggests that the P-h curve based approach for predicting HRB values is valid and accurate.

Figure 5 Comparison of the P-h curves of the two steel specimens from FE model and representative stress equations (a). Comparison between experiment and prediction Rockwell hardness value (HRB) with FE modelling for Carbon Steel 0.10 % C and Mild Steel (b).

Base on the concept prediction of hardness base on P-h curves an inverse material parameter estimation developed. The correlation between the HRB vs $\sigma_t$; HRB vs $E/\sigma_t$; and HRB/$\sigma_t$ vs $E/\sigma_t$; respectively. In this case, the HRB has shown a reasonable correction with all the three terms used, while the best fitting is found to be between HRB/$\sigma_t$ vs $E/\sigma_t$ with an effective representative strain of 0.033. The fitting is reasonable with the best correlation as:

$$HRB/\sigma_t = 0.0748 \ln (E/\sigma_t) - 0.2945$$ (4)

These relationships (Eqs.4) established allow direct hardness prediction from material properties. This is assessed using the two steel materials as example, the predicted HRB showed a similar level of agreement with the experimental data. In the case of the 0.1 C Steel, the HRB values is within 107% of the measured value; In the case of Mild steel, the HRB is within 102 % of the measured value. Similar agreement has been found in other materials (within 5% error range). This suggests that these can be used to predict the hardness values with sufficient accuracy with the measurement error ranges.

**Conclusions**

The main outcomes of work has formed a frame work of models to predict indentation P-h curves from constitutive material properties. In this work, FE model of Spherical indentation has been developed. The model was validated against published testing data. An approach to predict the P-h curves from constitutive material properties has been developed and evaluated. Two new approaches to characterise the P-h curves of spherical indentation have been developed and evaluated. One is the full curve fitting approach while the other is depth based approach. In the full curve fitting approach, the relationship between an effective representative stress with the first and second order coefficients of a polynomial fitting line of the P-h was established. In the depth approach the relationship between force and representative stress with varying representative strain has been established. Both approaches were proven to be adequate/effective in predicting indentation P-h curves. The approaches (i.e. predict hardness from P-h curves) established was successfully used to produce hardness values of a wide range of material properties, which is then used to establish the relationship between the hardness values (HRB) with representative stress.
References


