THE METHOD OF ACCOUNTING OF ELASTIC DEFORMATION OCCUR DURING THE AUTOMATED BALL INDENTATION TEST

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Abstract
The influence of indenter’s elastic deformation on the measurement of mechanical properties of materials by automated ball indentation test (ABIT) and its interpolation for different loads (from 0 to 10kN), modulus of elasticity (from 70 to 203 GPa), Poisson coefficient (from 0.275 to 0.340) are discussed. The logging of indentation load (applied directly to the indenter), indentation depth and plastic depth against the time is done using electrical method. It was also found by finite element analysis (FEA) that Poisson coefficient doesn’t affect the elastic deformation of indenter and the measurement process itself.

Keywords: ABIT, elastic deformation, indentation curve, FEA

1. INTRODUCTION
Mechanical tests are becoming more time-consuming and costly with the development of new materials and its processing methods [1]. This finding highlights the need not only in simple and rapid mechanical tests, but non-destructive as well. The hardness testing method introduced in engineering practice meets those requirements, establishing the relationship between hardness number and basic mechanical properties [2-3]. As follows from numerous theoretical and experimental studies, hardness tests provide much more information about the tested material during the ongoing recording of parameters of loading and unloading processes, resulting in the curve "force - indentation depth". This method is called "material testing using automated ball indentation" [4] and gives the most objective results in evaluation of the mechanical properties of materials and coatings. The curve "force - indentation depth" describes the characteristic behavior of the material during elastic, elastic-plastic and plastic deformations [5]. Theoretical background of the method is based on the fact that hardness is a characteristic of the surface tension and was designed by Brinell [6]. Other studies [7-9] analytically and experimentally confirmed the potential of the method and were accompanied with detailed solutions using the slip lines in calculations [10]. Based on [11] the stress-strain state of glass during the indentation using steel ball have been described in detail in [12-13], where the first set of equations was derived, including any stresses occurring in the glass by pressing a spherical indenter. With the advent of numerical calculation methods, particularly finite element method (FEM), the task has become much easier. These numerical solutions are recognized as a reference solution for the development of advanced analytical methodologies, calculations and indentation experiments performed at the macro-, micro- and nano-levels and usually are tied to specific experimental equipment and conditions. The first FEM solution for indentation of the ball into the elastic-plastic half-space was implemented in [14-15], but the work [16] is still a kind of manual for the indentation testing methods.

Fig. 1 ABIT device:
1 – Force developing mechanism, 2 – Adapter, 3 – Measuring device, 4 – Depth registering block, 5 – Ball indenter, 6 – Sample.
It should be noted that the number of papers on micro and nanoanalysis is much higher due to the popularity of these methods; then macromethods are less developed. In connection with the above, the improvement of express-methods of macroindentation is a scientific field that has great research potential.

The project uses a device that is described in [17-18] (Fig. 1). With its unique design it does not affect depth registering block, which registers one of the basic parameters (the depth of indenter penetration), what contributes to higher accuracy in comparison with analogues that have a longer measuring chain; is compact, automated and can be used along with various measuring systems. During the indentation process the indenter's elastic deformation ($\Delta$) occur which imparts an error to the measured values and, as a consequence, affects the final result (Fig. 2). The general methodology of accounting of the given error does not exist as each indentation device has its own boundary conditions, load apply and indenter fixation.

The aim of present work is calculation of elastic deformation of the ball indenter using the finite element analysis (FEA) and development of the method of its accounting during the indentation test done by device with special design. The method is based on the analysis of indentation process, specifically on the square spline interpolation of the values of the indenter's elastic deformation. The indenter with known diameter of 10 mm ($D$) is fixed on special holder and the interpolation is done at alternating values of the load ($P$), elastic modulus ($E$) and Poisson’s ratio ($\nu$), where indentation depth used in calculations represented as $h$.

2. MATERIALS AND METHODS

The algorithm of the study shown on Fig. 3, where the results of FEA obtained using ANSYS Multiphysics software are input data for consequent analysis using Maple mathematical tool. There are number of general requirements nowadays, which is necessary to follow during the modeling of indentation process:

1) The indentation task is contact one and assumes the use of finite contact elements;
2) The task can be simplified using axisymmetric models, because of its axial symmetry;
3) The testing material should be considered as elastoplastic and as close to the real as possible;
4) The indenter should be considered as deformable;
5) The load shall be applied gradually;
6) The plastic deformation in contact area during the indentation presupposes the specific behavior of testing material called «flow» or «depression».
7) The mesh in contact area should be reduced according to the power of the computer.

The axisymmetric (PLANE42) and contact elements (TARGET169, CONTA175) were used for the analysis. Testing material was considered as multilinear Isotropic with the introduction of basic points of $\sigma$-$\varepsilon$ diagram. The construction of FEM and consequent calculation is done using ANSYS (Fig. 4). The important feature of the model is that calculation is done for an indenter clamped in a special holder [19-20] allowing the recording of the diagram «load - indentation depth» automatically.

It is necessary to know the modulus of elasticity $E$, yield stress $\sigma_T$ and coefficient of hardenability $m$ in order to describe the behavior of the deformable body. The system of equations for the approximation of deformation diagram is as follows.

\[
\begin{align*}
\sigma &= E\varepsilon & \sigma < \sigma_T \\
\sigma &= \sigma_T \left( \frac{\varepsilon}{\varepsilon_T} \right)^m & \sigma \geq \sigma_T 
\end{align*}
\] (1)
Thus, it is possible to get the deformation curve sufficient for the consequent engineering calculations having the values of $E$, $\sigma$, and $m$ from the reference data sheets. For the given range of elastic moduli $70 \leq E \leq 203 \text{ GPa}$ considered in the present work, the linear increment $E_{i+1} = E_i + 7 \text{ GPa}$ is used (Fig. 5). The choice of this range is due to the coverage of most frequently used materials, such as carbon steels, cast irons, aluminum and titanium alloys, brasses.

### Results and Discussion

The von Muzes stress distribution diagram (Fig. 6) and plastic strain distribution diagram (Fig. 7) caused by the indentation process are obtained using ANSYS and show the maximum strain in a ball indenter (Fig. 6) and plastic strain is observed only in tested specimen (Fig. 7).

![Finite element model](Fig. 4)

![The range of elastic modules](Fig. 5)
The values for elastic deformation are calculated depending on such variable parameters as \( P \) (Fig. 8), \( E \) (Fig. 9) and \( \nu \) (Fig. 10), including the displacement of upper and lower nods of indenter, using ANSYS. Calculations for elastic deformation of indenter using the variable \( \nu \) (Poisson's ratio) do not show any influence on \( \Delta \), and so, did not included in the construction of the spline-surface represented on Fig. 11. The surface of values calculated using Maple according to methodology described in section 2 is shown on Fig. 11 representing the interrelation between \( P \) (0-10000 N), \( E \) (70-203 GPa) and \( \Delta \).
Indentation curve registered using the method described in section 1 represents the relationship between load and indentation depth including the calculated elastic deformation of an indenter (Fig. 12, x-green line) and without elastic deformation of an indenter (Fig. 12, +-red line). Hardness diagram «HB-e», including deformation in the indent e on the Fig. 13 is based on following relationships.

\[ HB = \frac{P}{\pi Dh} \]  

\[ e = \frac{h}{D} \]

3.1. Future work

For detailed considerations about accuracy of given indentation method, more experimental data extracted from testing materials in studied range of elastic moduli are required.

4. CONCLUSION

1) The software module for the square spline interpolation is developed using Maple computer algebra system, which allows to calculate the indenter’s elastic deformation for any variable values of the load, elastic modulus and Poisson's ration in any combination in the studied range: load from 0 to 10kN; elastic modulus from 70 to 203 GPa; Poisson coefficient from 0.275 to 0.340.

2) The correlation between the experimental results obtained without and with accounting the indenter’s elastic deformation is done, where the error of hardness measurement is in range of 0.72 – 1.39 % and its minimum values correspond with higher loads.

3) It was found that Poisson’s ratio doesn’t affect the change in elastic deformation of indenter in the studied range.

ACKNOWLEDGEMENTS

We would like to thank the SGS10/257/OHK2/3T/12 “Development of Materials for Biomedical Applications”, and the Innovation Center for Diagnostics and Application of Materials on CTU in Prague CZ.2.16/3.1.00/21037 for support.
LITERATURE

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