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ANALYSIS OF THE EFFECTS OF THE SAMPLE INCLINATION ON RESULTS OF VICKERS HARDNESS TESTING

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ABSTRACT

The objective of this paper is to analyse the influence of the specimen inclination on Vickers hardness measurements. A primary Vickers hardness testing machine (PVHM), and hardness reference test blocks with different hardness levels are used a different values of inclination angles for the tested specimens are obtained through a calibrated test rig. Theoretical and experimental analyses were conducted to evaluate the hardness tested samples tilting effects. The tests results were validated by analysis of variance (ANOVA). The results show that there is significant effect due to specimen inclination where the surface area of contact was found to be higher for tilted indentation and hence underestimates of hardness. Inclination is partially depending on the hardness level where the effects of inclination angle are reduced at higher levels of hardness values. Empirical formula was obtained to correlate between inclination angle and Vickers hardness error.

Keywords: Vickers hardness, tilting effects, indenter inclination.

INTRODUCTION

The Vickers test is the standard method for measuring the hardness of metals, particularly. Those with extremely hard surfaces: the surface is subjected to a standard pressure for a standard length of time by means of a pyramid-shaped diamond with a vertex angle of 136^o.

The diagonal of the resulting indentation is measured under a microscope. The full load is normally applied for 10 to 15 seconds (ISO, 2005). The Vickers hardness is the quotient obtained by dividing the kgf load by the square mm area of indentation. Only a few micron differences in diagonal length could cause significant error in HV scale. There are several factors that may affect the Vickers results. In order to improve the accuracy of material characterization, it is required to consider all the affecting parameters in calculations. Some of the various factors that should be taken into account in Vickers are purely geometrical, such as surface roughness, indenter geometry, and tip rounding. The influence of surface roughness has been reported in several papers (EA, 2005). The geometry of indenter and the tip rounding have also been found to be important in Vickers tests.

There is another geometrical source of error that seems to have been neglected. The assumption that the axis of the indenter is perpendicular to the surface being indented is important when either the sample surface is tilted or the indenter axis is tilted with respect to the indentation.

The aim of the submitted work was to study the effect of sample surface tilting on the results of sample testing with diamond Vickers indenter is addressed from a geometrical point of view. Sample inclination is one of the parameter which effects on the error percentage of HV values, and it doesn't subject to sufficient study to detect how it can affect the measured hardness values. The results of the experiments were analyzed and evaluated by one factor analysis of variance (ANOVA).

MATERIALS AND METHODS

Equipment and CRMs

A primary Vickers hardness standard machine (PVHM) was used to perform the experiments. PVHM was provided by a calibrated test rig which was utilized as a sample base for the variation of inclination angles under investigation. Olympus stereo microscope was used to measure the indentation diagonals (Fig.1).

Certified reference materials (CRM) in the form of hardness test blocks were used as a standard for investigation.

Geometrical analysis for the contact between a pyramidal indenter and tilted sample surface.

The ideal four-sided pyramid diamond Vickers indenter is a perfect square base pyramid with an angle θ (Satoshi *et al*., 2006) (typically 68.00◦) between the central axis and each face .This model also assumes that all four faces

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Fig.1. Stero microscope and PVHM.

meet at a singular point (that is, the line of conjunction length is zero).

Area function for pyramidal indentation into untitled samples

Ideally, in Vickers the real contact depth is h_c, the real contact projection area is as follows (Fig. 2).

$$HV = \frac{F}{A_s} = \frac{2F.\sin\left(\frac{\alpha}{2}\right)}{d^2} \quad (1)$$

Where A_s is the contact area when the displacement equals h_c (Fig 1)

$$A_s = 24.5h^2{}_c \quad (2)$$

$$d = 2\sqrt{2}.a.\sin\left(\frac{\alpha}{2}\right) \quad (3)$$

$$d = 2\sqrt{2}.\frac{h}{\cos(\theta)}.\sin\left(\frac{\alpha}{2}\right) = 2.\sqrt{2}.h_c.\tan\left(\frac{\alpha}{2}\right) \quad (5)$$

$$A_{real} = \frac{1}{2}.\left(2.\sqrt{2} \times h \times \tan\left(\frac{\alpha}{2}\right)\right)^2$$

$$= 4.h_c{}^2 \times \tan^2\left(\frac{\alpha}{2}\right) = 4 \times \left(\frac{d}{7}\right)^2 \times \tan^2\left(\frac{\alpha}{2}\right) \quad (6)$$

Area function for pyramidal indentation into titled samples

When the axis of the indenter is loading on the surface of the sample un-vertically, the real contact projection area can't be calculated by Eq. (6). Since the axis may be inclined in the different orientations, it'll induce the calculation of the area to be very complicated. Therefore, the calculation method of the real contact projection area As is introduced only for the angle ζ between the actual axis in the axial middle section of the opposite sides at the bottom of the Vickers indenter and the ideal axis of the indenter assuming The rotation angle specifies the direction of the tilt with respect to one of the edges of the pyramid is zero, as shown in figure 3.

When the indented depth is h_c, the real contact projection area can be calculated as follow.

$$A_1 = \frac{(a_1 + b_1) + (a_2 + b_2)}{2}$$

$$a_1 = \frac{h_c \tan\left(\frac{\alpha}{2}\right)}{\left[\left(1 - \tan(\theta) \times \tan\left(\frac{\alpha}{2}\right)\right)\cos\left(\frac{\alpha}{2}\right)\right]}$$

$$b_1 = \frac{h_c \tan\left(\frac{\alpha}{2}\right)}{\left[\left(1 + \tan(\theta) \times \tan\left(\frac{\alpha}{2}\right)\right) \times \cos\left(\frac{\alpha}{2}\right)\right]}$$

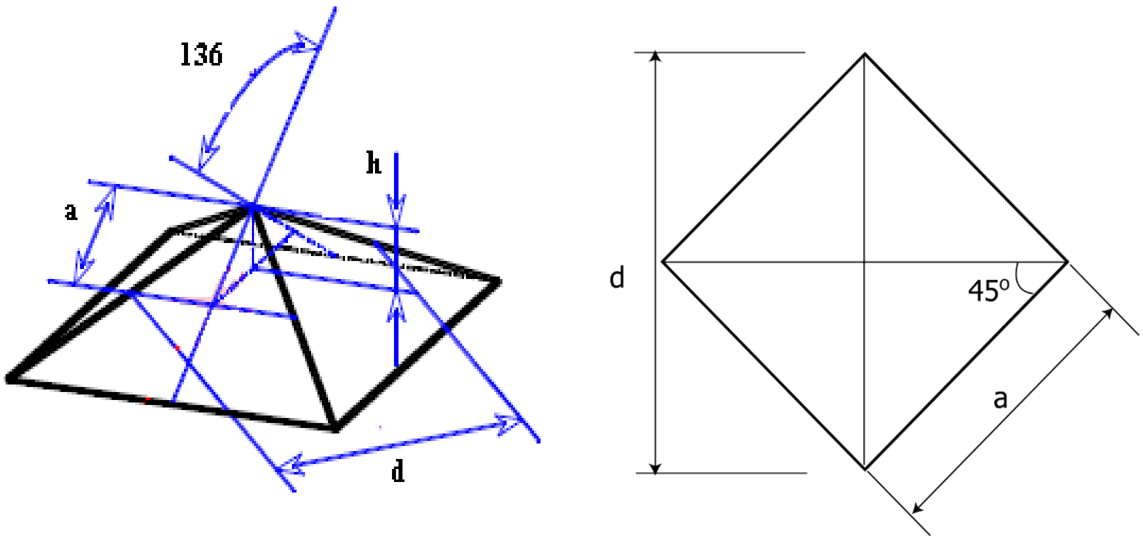

Fig. 2. Geometrical parameters of Vickers indenter and untitled contact area.

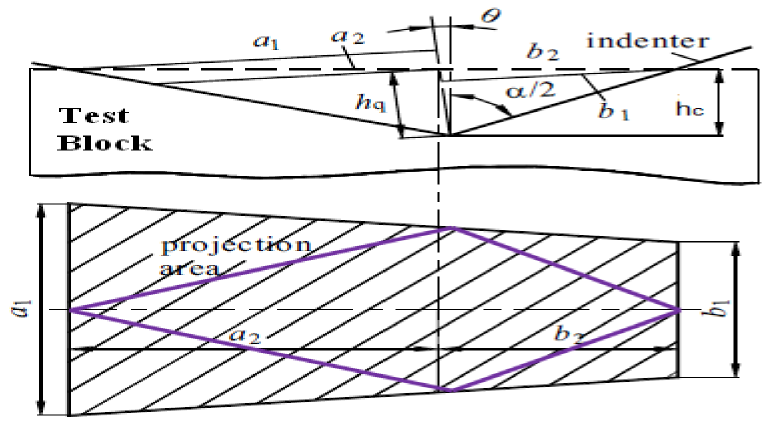

Fig. 3. Schematic of contact between indenter and tilted sample.

$$a_2 = \frac{h_c \tan\left(\frac{\alpha}{2}\right)}{\left[\left(1-\tan(\theta)\times\tan\left(\frac{\alpha}{2}\right)\right)\times\cos^2\left(\frac{\alpha}{2}\right)\right]} \quad (10)$$

$$b_2 = \frac{h_c \tan\left(\frac{\alpha}{2}\right)}{\left[\left(1+\tan(\theta)\times\tan\frac{\alpha}{2}\right)\times\cos^2\left(\frac{\alpha}{2}\right)\right]} \quad (11)$$

$$A_\theta = \frac{24.5\times h^2{}_c}{1-3\tan^2(\theta)\tan^2\left(\frac{\alpha}{2}\right)-2\tan^3(\theta)\tan^3\left(\frac{\alpha}{2}\right)} \quad (12)$$

$$A_\theta = \frac{0.5\times d^2}{1-3\tan^2(\theta)\tan^2\left(\frac{\alpha}{2}\right)-2\tan^3(\theta)\tan^3\left(\frac{\alpha}{2}\right)} \quad (13)$$

Theoretical calculation for contact area and hardness for tilted and untitled

For ideal case of indentation without samples tilt, the surface area of the pyramidal indenter would be a four sided figure with equal sides.

Ideal surface area can be calculated by eq. No 1 or 2 at angle of inclination 0° and the inclined surface area can be calculated by eq. No 13 after measurement of the indentation diagonals produced from testing assuming the angle of inclination from 0.2° up to 1.5°.

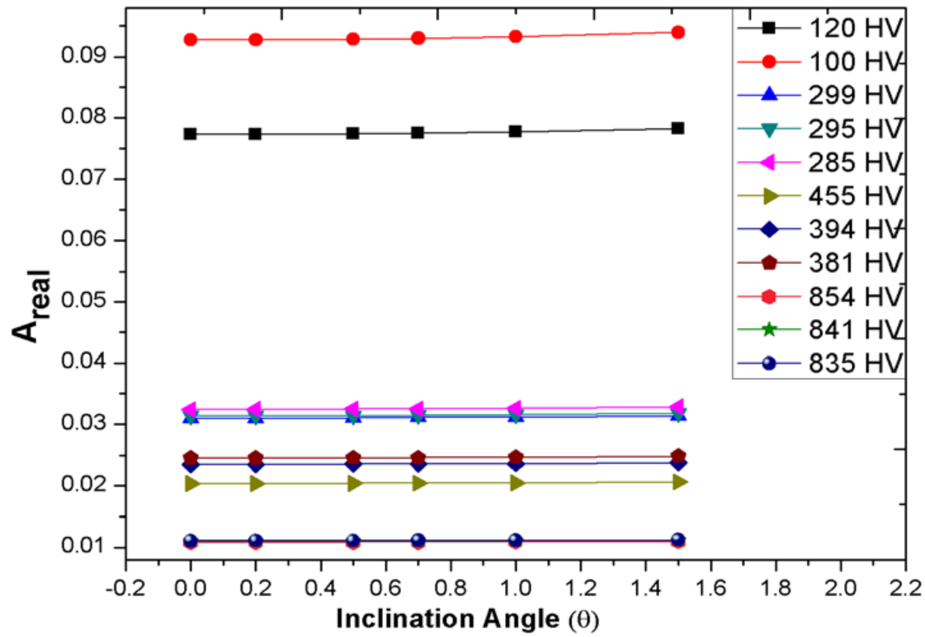

Fig. 4. Theoretical calculated mean area of contact at various hardness levels.

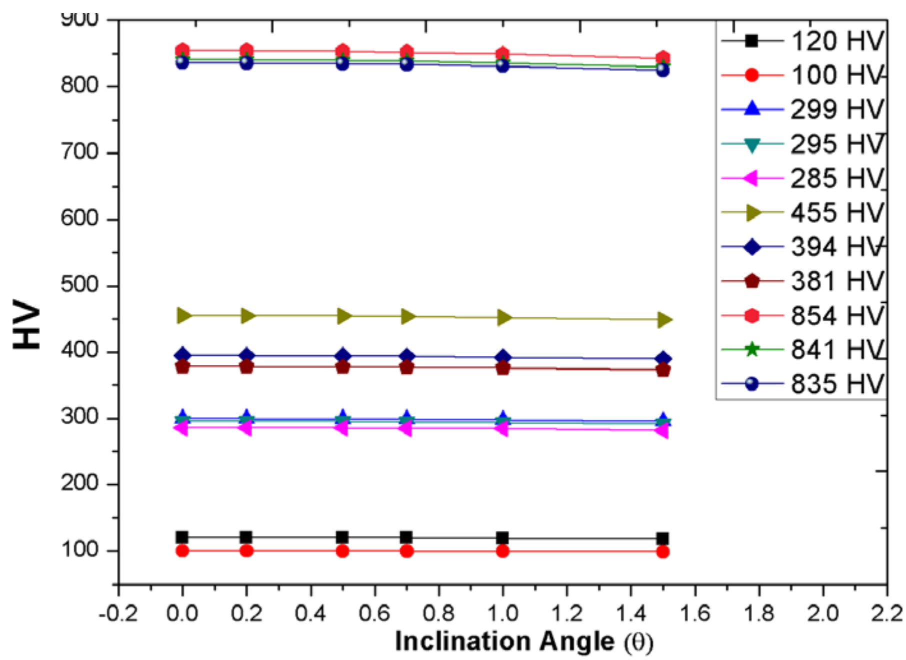

Fig. 5. Theoretical calculated hardness at various hardness levels.

It was noted that the contact area is significantly affected by the inclination angle where increasing the inclination of the surface under test tends to overestimates of contact area and hence under estimates of hardness as shown from the following figures. Figures 4 and 5 shows the theoretical inclination effects on the contact area and hardness.

Experimental procedure

PVHM which has been evaluated through comparison with Physikalisch-Technische Bundesanstalt (PTB) primary Vickers hardness testing machine (Menalo *et al*., 2010; Mohammed *et al*., 2010). A calibrated inclination test rig is used to imply the various angles. Variation of the angle will be done by micromere which is inserted in

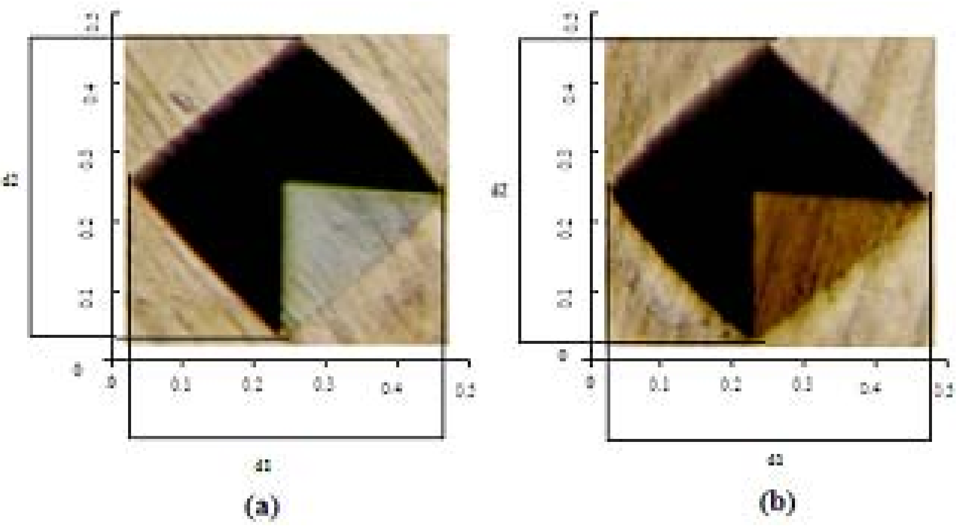

Fig. 6. Scanned impression of indentations for (a) the untitled sample and (b) the one degree tilted.

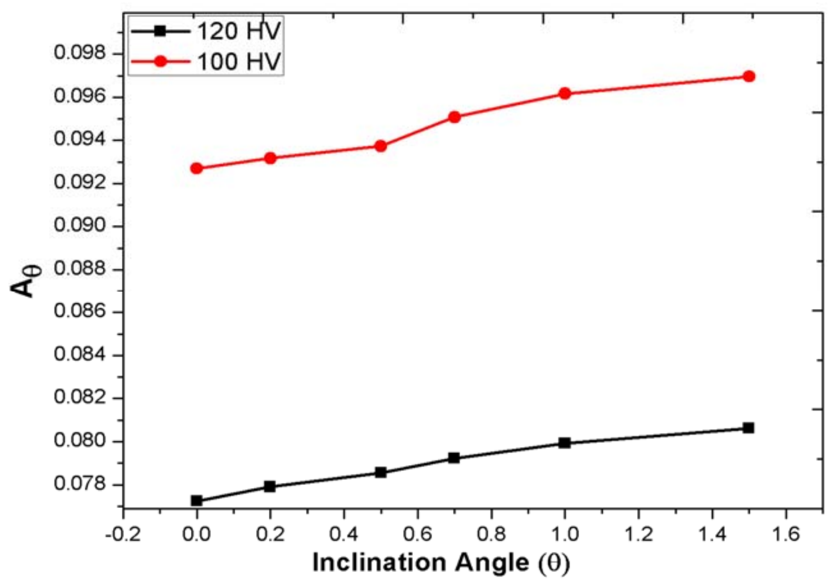

Fig. 7. Experimental surface area at hardness level (120,100) HV.

the test rig. The selected angles which were been investigated are 0.2 º, 0.7 º, 0.5 º, 1 º and 1.5 º. The experiments started by measuring the hardness of standard blocks at 0 º of inclination, the hardness results at this state will be used as reference to calculate the error for other measurements at varying inclination angle using test rig.

After area function calibration, the same test specimen was mounted on different degree angle values (0.2, 0.5, 0.7, 1, and 1.5) and five indentations were made. The scanned impressions of indentations with nominal diagonals are shown in Fig 6 for both untitled and on degree tilted samples. It can be seen that the indentations on tilted sample are not a right square anymore, and which have slightly higher projected area.

RESULTS AND DISCUSSION

From the experiments the surface area of contact was found to be higher for tilted indentation (see Figs. 7 to 10) and hence underestimates of hardness (see Figs. 11 to 14). The test results analysis shows that the effects of inclination is partially depending on the hardness level and the effects of inclination angle is reduced at higher level of hardness values.

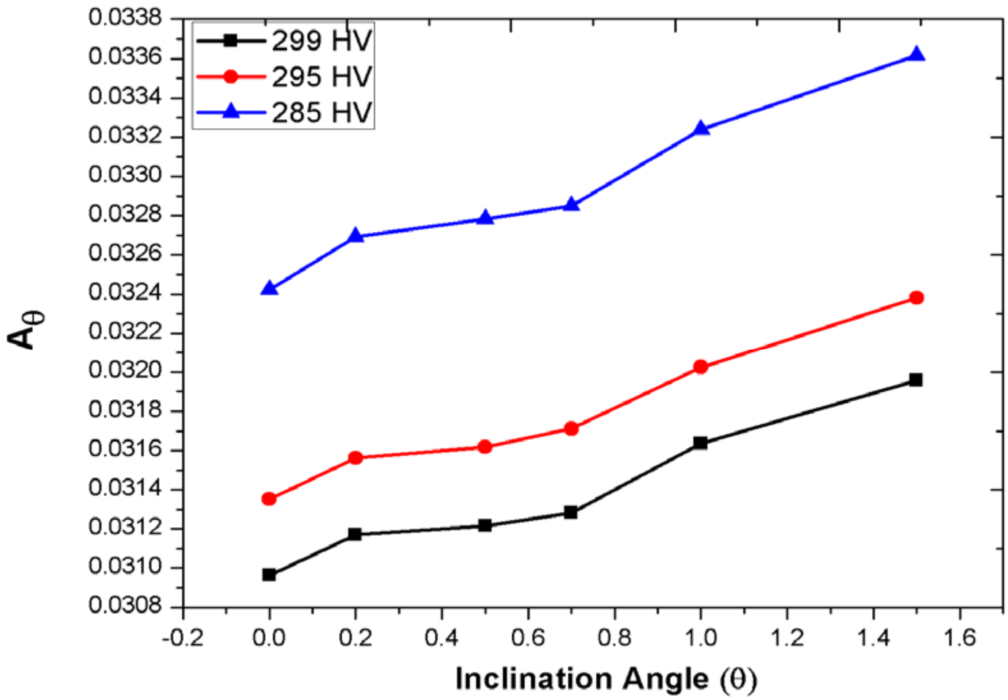

Fig. 8. Experimental surface area at hardness level (299, 295, 285) HV.

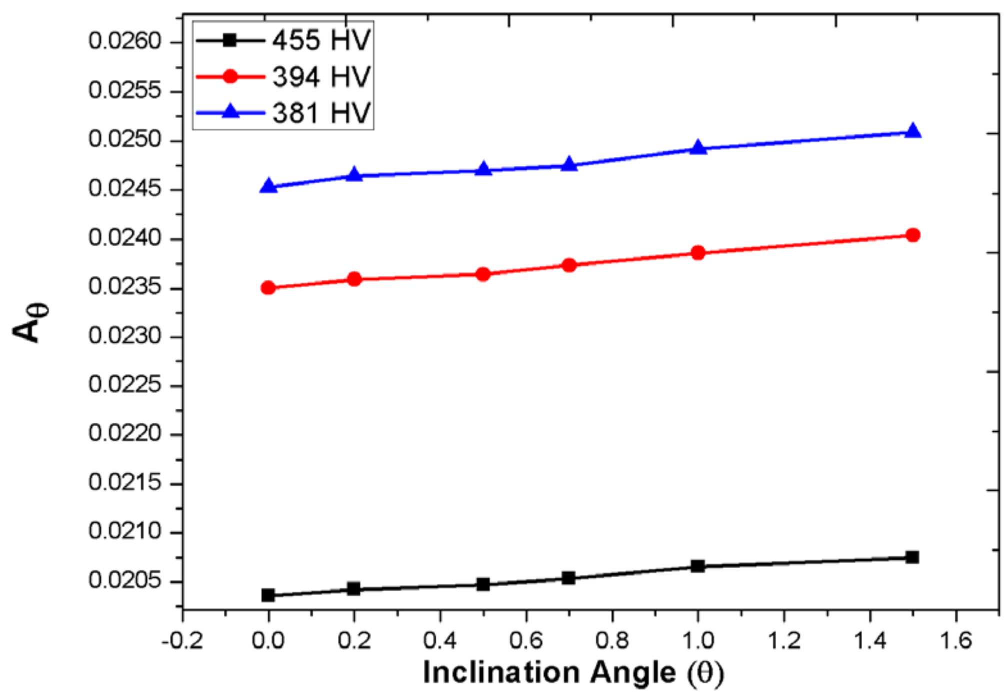

Fig. 9. Experimental surface area at hardness level (455, 394, 381).

The figures shows that the effects of inclination can be significantly increased at low hardness levels, for tilting angle 1° at hardness level 100HV, 120HV the hardness results will be reduced by more than 3.5%, for hardness level 285HV, 295HV and 299HV the hardness results will be reduced by more than 2%, for hardness level 835HV, 841,854HV the effects of inclination can be significantly reduced where the error doesn't exceed 1%. For tilting angle 1.5° at hardness level 100HV, 120HV the hardness results will be reduced by more than 4%, for hardness

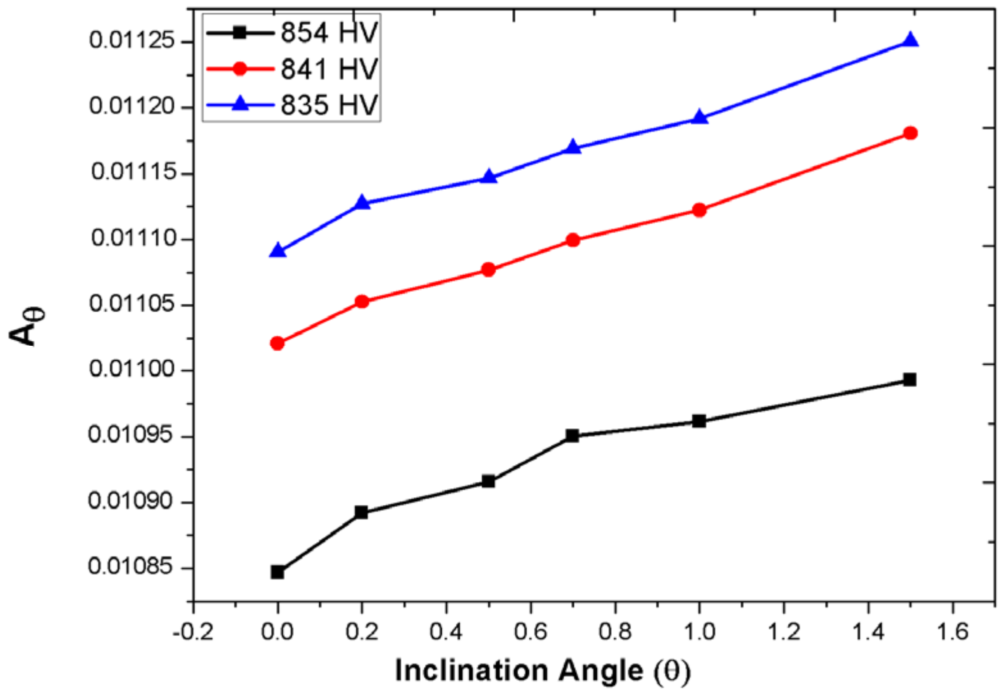

Fig. 10. Experimental surface area at hardness level (854, 841, 835) HV.

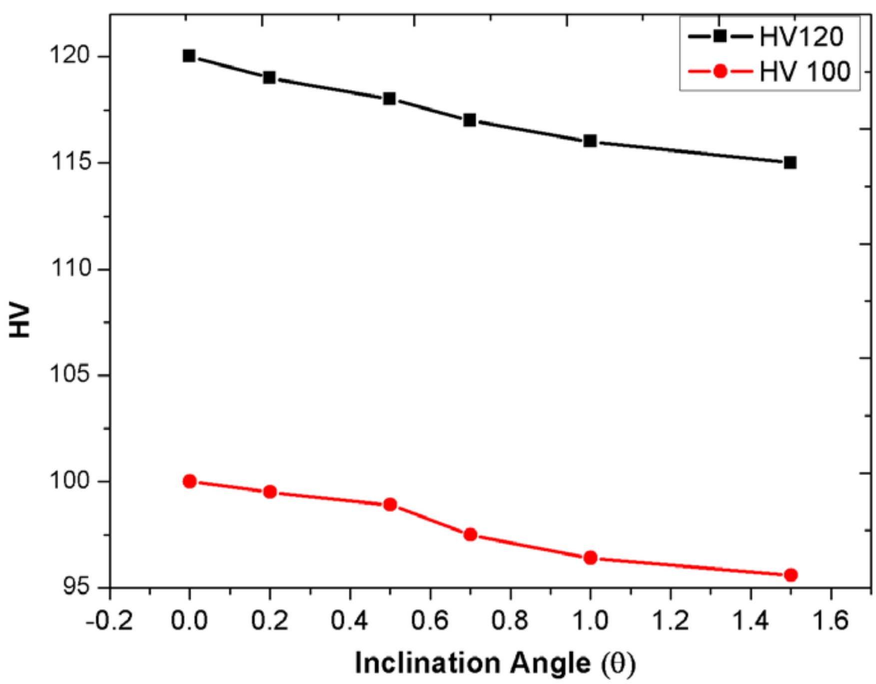

Fig. 11. Experimental hardness at hardness level (120, 100) HV.

level 285HV, 295HV and 299HV the hardness results will be reduced by 3%, for hardness level 835HV,841,854HV the effects of inclination can be significantly reduced where the error doesn't exceed 1.2% (see Figs. 7 to 14).

STATISTICAL ANALYSIS

In this work all empirical model was developed using the values obtained from experimental investigation for hardness testing of metallic materials. The empirical

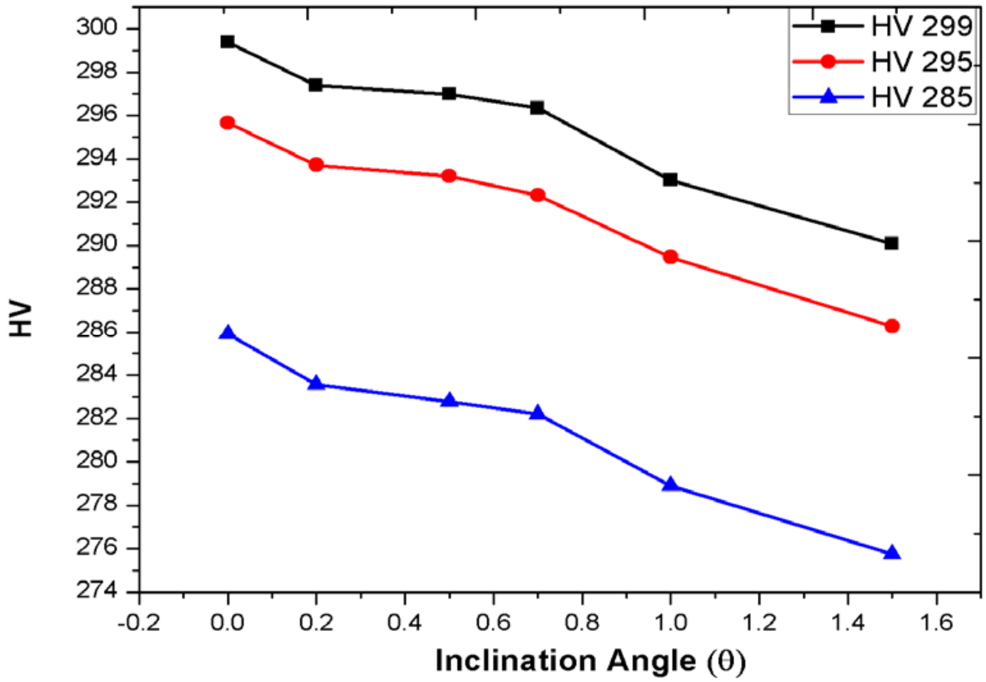

Fig. 12. Experimental hardness at hardness level (299, 295, 285) HV.

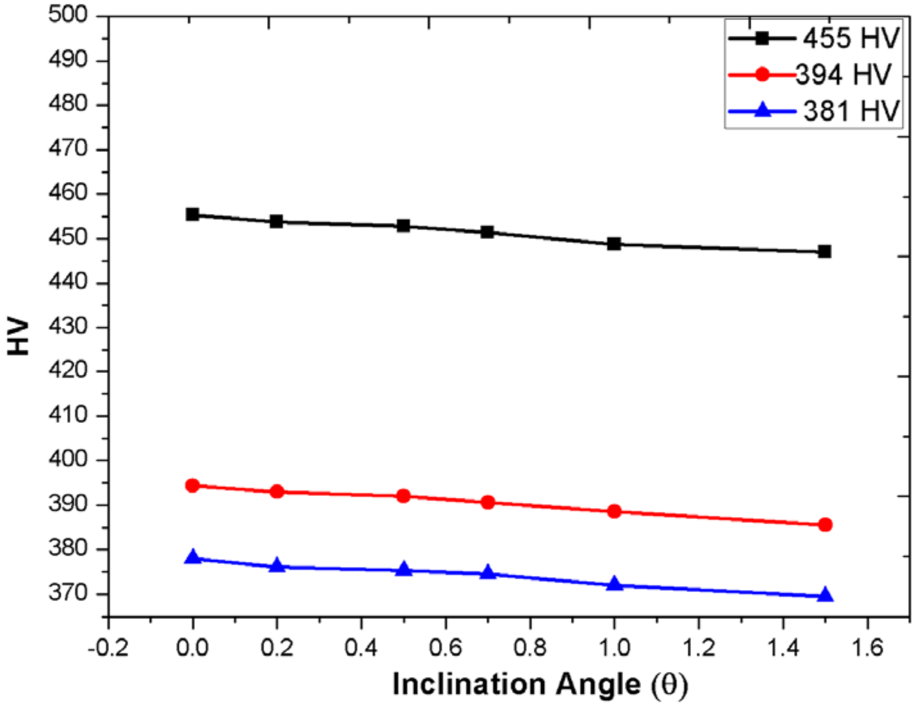

Fig. 13. Experimental hardness at hardness level (455, 394, 381) HV.

model was used to predict the effects of sample tilting on the hardness testing results. OriginPro8 statistical analysis software was used in the present case to establish an empirical correlation between sample under test titling and the produced error of measurements expressing the outputs in the linear form as shown in Equation 15**.** Curve fitting and ANOVA statistical methods is utilized for the purpose of results analysis. From experiments it was noted that there are significant dependence of hardness level on the produced tilting error.

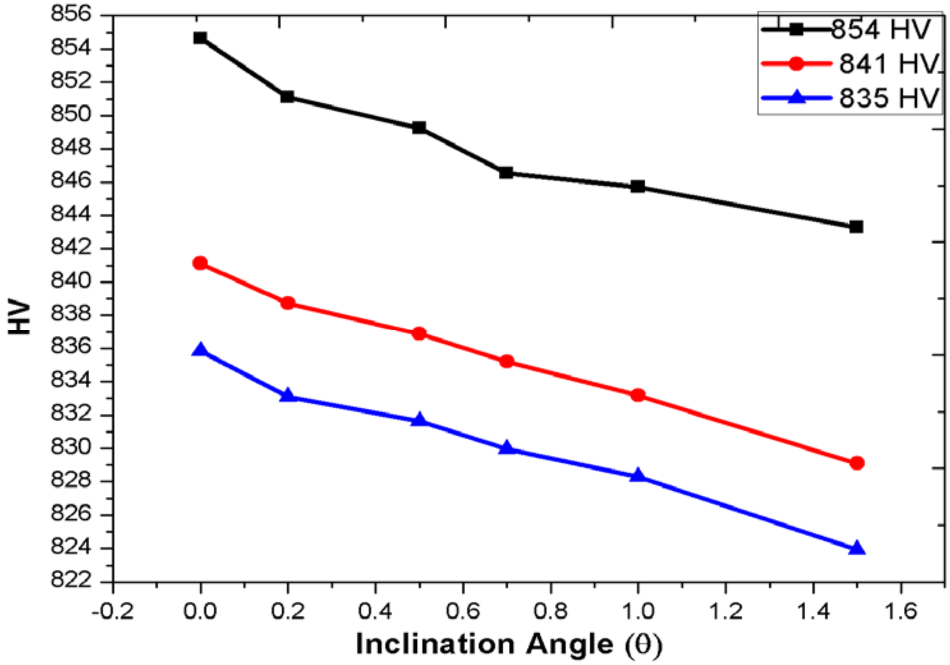

Fig. 14. Experimental hardness at hardness level (854, 841, 835) HV.

Empirical model can be formulated as follow,

$$HV_{error\,\%} = F(HV, \theta) \quad (14)$$

From statistics the empirical equation was as follow,

$$HV_{error\,\%} = -2.89169 \times Angle + 0.00259 \times HV \times Angle \quad (15)$$

Accuracy and validity of model

The model was validated by comparing the predicted values with experimental values. The predicted values were found to compare favorably with experimental values the mean percentage error Determined using Equation 15 were found to be ranging from (0.01 to 0.4) % in hardness .The empirical model developed is reasonably accurate to predict the influence on sample tilting on the measured hardness value.

Theoretical and experimental investigation for the amount of error due to surface tilt for the Vickers hardness indenter can be observed that Vickers hardness testing indenter is sensitive to this source of error. There are slightly differences between the test results produced from theoretical and experimental investigations this difference due to the partial effects of material hardness levels. The effects of inclination can be significantly increased at low hardness levels where it can reduced the hardness test result up to 3.5 %, but at the very high hardness levels the reduction in hardness values doesn't exceed 1%, this effect due to the great effect of sliding resistance for the inclined indenter at higher levels of hardness.

CONCLUSION

Theoretical and experimental study for the effect of surface tilt on results of Vickers hardness tests is conducted. The true projected and surface area for indenter and indented zone based on the exact three dimensional geometry of the contact zone between the indenter and test sample is calculated. Geometrically there is significantly affect due to surface inclination of the sample under test a correction factor can be included. It is found from the experiments the surface area of contact was found to be higher for tilted indentation and hence underestimates of hardness. The test results analysis show that the effects of inclination is partially depending on the hardness level and the effects of inclination angle is reduced at higher level of hardness values. The empirical model developed is reasonably accurate to estimate the mean effect of sample inclination of the results of hardness testing. The model performance was found to be satisfactory and show good predictability. It is hoped that this produced empirical model for computing predicted inclination effect will be useful and serve as guide for correcting the unvertical Vickers hardness testing results.

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