Imprints method for determining the ratio of macro- and microhardness when tested for Vickers hardness

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Abstract. The method has been developed for calculating microhardness values under different loads, with known macro-hardness as well as with macro-hardness and microhardness with a single microhardness value, based on comparing the size of non-recovered and recovered imprints – imprints method (IM). The method correctness test for different materials in a wide range of hardness values – 80 ... 1500 HV, at different indentation loads, was performed. High accuracy of the developed method is shown.

Keywords: macrohardness, microhardness, indentation size effect, the imprints method, recovered and non-recovered imprints.

1. Introduction.

Depending on the applied load \( F \) and the indenter penetration depth \( h \), in accordance with ISO 14577-1: 2002 hardness is divided into «Macro-range – \( 2N \leq F \leq 30 \text{kN} \); «Micro-range – \( F < 2H; h > 0.2 \text{ \mu m} \); «Nanoscale – \( h \leq 0.2 \text{ \mu m} \). According to ISO 6507-1: 2005 (Test method (IDT) micro-hardness area lies within the load limits from 0.09807 to 1.961 N.

When determining the microhardness (\( HV_{\text{micro}} \)) by Vickers in the micro-range, a «size effect» is observed (Indentation Size Effect) [1-3], manifested in the fact that the values of hardness, determined by the recovered imprint (i.e. after removing the indenter from the test sample), depend on indentation load, and they are higher, the smaller the load. The size effect is due to the fact that the elastic deformation of the material, developing with the indenter inserting and disappearing after its removal, is not taken into account when assessing hardness. Therefore, the microhardness values are greater than the macro-hardness (\( HV_{\text{macro}} \)). In the macro-hardness range hardness values, on the contrary, are practically independent of the load [1, 2] due to a very small magnitude of elastic deformation. This common pattern has been proved in our work.

Establishing the connection between \( HV_{\text{macro}} \) and \( HV_{\text{micro}} \), as well as between the \( HV_{\text{micro}} \), is measured with different loads, important for solving various scientific and practical problems. Its absence makes inconsistent microhardness values not only of different materials, but even of the same material, if the tests are performed in the micro range under different loads. It is also impossible to compare the hardness measured in the micro and macro ranges.

To establish the dependencies between the values of \( HV_{\text{macro}} \) and \( HV_{\text{micro}} \) a number of methods have been proposed [4–8], in which the size effect, when calculating the hardness, was changed by some correction, taking into account the elastic recovery of the imprint and reducing the value of microhardness, obtained experimentally, or power dependency between the effort of indentation and the size of the recovered imprint and the value of the non-recovered imprint [5]. However, in [1, 2], these methods are evaluated as incorrect. A common drawback of the methods in [4–8] is the erroneous...
assumption of the correction parameters constancy for the material. In fact, as our preliminary tests have shown, these parameters depend on the indentation conditions and may be 1.5…2 times different for one material. This leads to the uncertainty of the obtained results when calculating the values of hardness and, thus, to the inexpediency of using these methods. They are not considered in this paper.

The purpose of this work is to develop a method that establishes an analytical relationship between $HV_{\text{macro}}$ and $HV_{\text{micro}}$ during the Vickers pyramid indentation – imprints method (IM).

2. Materials and research methods.

There were researched materials, the hardness of which varies in a wide range from 80 to 1500 HV. These are solid ductile materials: hard alloy VK6 (in wt.%; 94 WC, 6 Co) (~1500 HV) and high speed steel HS 18-0-1 after quenching and tempering (~800 HV), as well as ductile materials with low hardness technically pure iron and copper (~80…100 HV) and annealed HS 18-0-1 (~250 HV) (table 1.). The surface sample preparation for testing was performed on the company «Struers» (Denmark) equipment. While preparing samples there was used fine grinding and polishing applying diamond abrasives of different dispersion, eliminating plastic deformation and surface hardening.

Table 1. Macro-and microhardness of the studied materials.

| Load (g) | Cu | Fe | HS 18-0-1 ann. | HS 18-0-1 quen.+temp. | VK6 |
|----------|----|----|----------------|-----------------------|-----|
| 5000 (macro-range) | 93 | 86 | 234 | 741 | 1490 |
| 2000 | 93 | 86 | - | - | - |
| 1000 | 93 | 86 | 234 | 741 | 1490 |
| 500 | 94 | 86 | 238 | 753 | 1485 |
| 200 | 96 | 87 | 249 | 795 | 1469 |
| 100 | 100 | 104 | 256 | 805 | 1594 |
| 50 | 102 | 106 | 262 | 827 | 1651 |
| 25 | 104 | 122 | 288 | 890 | 1754 |
| 10 | 103 | 139 | 316 | 927 | 1886 |

Vickers hardness was determined in accordance with the Russian and International Standards. For macro-range according to ISO 6507-1: 2005; for micro-range according to GOST 9450-76 (state standard of Russia). Tests were carried out on micro-hardness meter «Duramin-2» («Struers», Denmark), with the load range from 0.098 to 19.61 N (10 to 2000 g; indentation force in the gf used in our study, denoted as $P$ in contrast to the adopted standards – $F$ in kg or N).

Hardness at a given load was determined by the average value after six tests. The relative error in hardness measurement with the reliability of 0.95 did not exceed 3%.

The diagonal of the recovered (after removal of the load and removal of the indenter from the test sample) imprint $d$ was measured with an error of ±0.1 µm and for each material at a given load was estimated as the average of six measurements results.

Non-recovered imprint $D$ diagonal was calculated, on the basis of the fact that for any load, the indenter penetration depth, estimating the value of the non-recovered imprint, corresponds to a load-independent hardness, i.e., macro-hardness $HV_{\text{macro}}$. Thus, the magnitude of the diagonal non-recovered imprint $D$ is a design one:

$$D = \left( \frac{1.854F}{HV_{\text{macro}}} \right)^{1/2} [\text{mm}]$$

where $F$ – test load (applied) in kg; $HV_{\text{macro}}$ – macrohardness.

The approximation of experimental data was performed using Microsoft Office Excel 2007. Verification of the developed method correctness was performed using the data obtained in this study and given in the literature.

3. Results and discussion.
Values of macro- and microhardness are given in Table 1. When measuring hardness in the range of 10-200 g (load in determining the microhardness of ISO 6507-1: 2005) for all the materials studied there was observed dimensional effect (see Table 1). Figure 1 shows the typical hardness dependency on the applied load for the alloy VK6.

**Figure 1.** Dependency of the VK6 alloy hardness (recovered imprint) on the test load.

The developed method is based on a comparative analysis of the recovered and non-recovered imprints in the microhardness range at different indentation loads. Let $D$ be the diagonal of the imprint obtained by embedding the indenter to a depth of $h_1$ under load $P$ (Figure 2a). After removing the load as a result of the elastic aftereffect, the depth of the imprint will reduce to $h_2$, which corresponds to the diagonal of the recovered imprint $d$ (Figure 2b).

**Figure 2.** Non-recovered (a) and recovered (b) imprints: $P$ – test load; $h_1$, $h_2$ and $D$, $d$ – depths and diagonals of non-recovered and recovered imprints, accordingly.

**Figure 3.** Schematic diagram «$F$ - (D, d)».

To establish the relationship between $HV_{macro}$ and $HV_{micro}$ for all materials under study there were built diagonals $D$ and $d$ size dependencies on the indentation force – diagram «P-(D, d)», the schematic diagram of which is shown in Figure 3.

All $d$ values were determined experimentally. The value of $D$ is calculated, its estimating is based on the fact that the diagonal of the imprint with the embedded indenter characterizes the true hardness regardless of the load. The position of the true hardness was postulated in [1], in which the curve of hardness dependency on the load is approximated by hyperbole. Crossing the horizontal asymptote of
the hyperbole with the ordinate axis (see figure 1), shows the true hardness value, corresponding to $HV_{\text{macro}}$.

Ascending branch of the hyperbole describes $HV_{\text{micro}}$, depending on the test load, and its part at the indenter penetration depth $h \leq 0.2 \ \mu m$, and, thus, very small values of $d$, (in the limit, at $d \rightarrow 0$; $HV \rightarrow \infty$) are characterized, in accordance with ISO 14577-1:2002, nanohardness.

The value $D$ calculation is based on standard methods for estimating the hardness of the recovered imprint in which hardness is evaluated not by the imprint diagonal, but by the indenter penetration depth under load. According to GOST 9450-76 (state standard of Russia) hardness is indicated by $HVh$, and for Vickers indenter is calculated by the Eq. (2):

$$HV_h = \frac{0.03784F}{h^2} \quad (2)$$

According to ISO 14577-1:2002, hardness is denoted by $HM$ – the number of Martens hardness; and for the Vickers indenter is calculated by the Eq. (3):

$$HM = \frac{F}{26.43h^2} \quad (3)$$

In Eqs. (2) and (3) $F$ – load in kgf; $h$ – depth of indenter introduction under load in mm ($h=h_1$ in figure 2a). For the Vickers pyramid $D=7h$ (up to the fourth decimal place), replacing the values of $h$ in the Eqs (2) and (3) with $D/7h$, we obtain:

$$HV_h = HM = \frac{1.854F}{D^2} = HV_{\text{macro}} \quad (4)$$

Thus, the values of $HVh$ and $HM$ correspond to the material hardness determined by Vickers in accordance with ISO 6507-1:2005, i.e. $HV_{\text{macro}}$, and the diagonal of the unrestored imprint $D$ is determined by the penetration depth of the indenter $h$, depending on the test force $F$ and the hardness of the material – $HV_{\text{macro}}$. The resulting output allows us to calculate the values of $D$ in the micro-range by the Eq. (1), if the material $HV_{\text{macro}}$ (table 1) and the applied force are known. The calculated values of the diagonals of the recovered imprint $D$ and the experimental values of the restored imprint $d$ of the materials under study, depending on the load, are given in table 2.

**Table 2.** Diagonals of restored ($d$) and non-restored imprints ($D$) dependency on the indentation load.

| Material ($HV_{\text{macro}}$, kg mm$^{-2}$) | Imprint diagonal | The magnitude of the diagonal µm, depending on the load, g |
|---------------------------------------------|------------------|----------------------------------------------------------|
| $D$ | $d$ | 10 | 25 | 50 | 100 | 200 | 500 | 1000 | 2000 |
| Cu (93) | | | | | | | | | |
| $D$ | 14.1 | 22.3 | 31.5 | 44.6 | 63.1 | 99.7 | 141.0 | 199.4 |
| $d$ | 13.4 | 21.1 | 30.2 | 43.1 | 62.1 | 99.5 | 141.2 | 199.5 |
| Fe (86) | | | | | | | | | |
| $D$ | 14.7 | 23.2 | 32.8 | 46.4 | 65.6 | 103.7 | 146.6 | 207.3 |
| $d$ | 11.9 | 19.5 | 29.5 | 42.3 | 65.4 | 103.6 | 146.8 | 207.6 |
| HS 18-0-1 ann. (250) | | | | | | | | | |
| $D$ | 8.9 | 14.0 | 19.8 | 28.0 | 39.6 | 62.7 | 88.6 | – |
| $d$ | 7.7 | 12.7 | 18.8 | 26.9 | 38.6 | 62.4 | 89.0 | – |
| HS 18-0-1 | | | | | | | | | |
| $D$ | 5.0 | 7.9 | 11.1 | 15.8 | 22.3 | 35.2 | 49.8 | – |
| quen.+temp. (785) | | | | | | | | | |
| $d$ | 4.5 | 7.2 | 10.6 | 15.2 | 21.6 | 35.1 | 50.0 | – |
| VK6 (1490) | | | | | | | | | |
| $D$ | – | 5.6 | 7.9 | 11.2 | 15.8 | 24.9 | 35.3 | 49.9 |
| $d$ | – | 5.0 | 7.3 | 10.6 | 15.2 | 25.1 | 35.3 | 49.5 |

The microhardness values used for the calculation of $D$ are given in table 1.

$(D$ and $d$) imprints diagonals values dependencies on applied forces ($P$) – curves $P$–$(D, d)$ (figure 3) and are approximated by power functions:

$$d = A_d \cdot P^z \quad (5)$$

$$D = A_D \cdot P^{0.5} \quad (6)$$

Where: $P$ is test load (g); $d$ and $D$ – experimental and calculated sizes of diagonals (µm), recovered and non-recovered imprints, respectively; $A_{(D, d)}$ – the constants of the material, depending on its hardness, herein $A_D>A_d$; since in the range of micro-hardness $D>d$ (see figure 2 and table 2.); the greater $A_D$ and $A_d$ values the lower the hardness of the material, i.e. more than the imprint diagonal (table 3); $z$ – a fractional exponent that depends on the material properties.
Herein $z > 0.5$, since in the microhardness range $A_D > A_d$ and $D > d$, but at the range boundary $\langle HV_{\text{macro}} - HV_{\text{micro}} \rangle$ both diagonals should become equal $(D \approx d$ see figure 3). This is only possible provided the load increases, $d$ increases faster, than $D$. For the Eq. (6) the power index is constant for all materials ($z = 0.5$), which gets out of independence of true hardness $HV_{\text{macro}}$ from the indentation effort. In fact, Eq. (6) is formula (1) conversion, where

$$A_D = \left( \frac{1.854 F}{HV_{\text{macro}}} \right)^{1/2}$$

(7)

In table 3 there are given the values of constants $A_d$, $A_D$ and fractional exponent $z$ of approximating functions (5) and (6).

| Table 3. Diagonals of recovered and non-recovered imprints dependency on the indentation load. |
|-----------------------------------------------|
| Material | Diagonal | $d = A_d P^{z}$ | $D = A_D P^{0.5}$ | Correlation coefficient, $R^2$ |
| Cu | d | 4.0680 $P^{0.5139}$ | | 0.9999 |
| D | 4.4585 $P^{0.5}$ | | 1 |
| Fe | d | 3.2947 $P^{0.5576}$ | | 0.9993 |
| D | 4.6359 $P^{0.5}$ | | 1 |
| HS 18-0-1 ann. | d | 2.2684 $P^{0.5353}$ | | 0.9997 |
| D | 2.8032 $P^{0.5}$ | | 1 |
| HS 18-0-1 | d | 1.3344 $P^{0.5265}$ | | 0.9999 |
| quen.+temp. | D | 1.5753 $P^{0.5}$ | | 1 |
| VK6 | d | 0.8752 $P^{0.5402}$ | | 0.9999 |
| | D | 1.1158 $P^{0.5}$ | | 1 |

$A_D$ and $A_d$ parameters are constants of materials, depended on microhardness. For $A_D$ this dependency outcomes from Eq. (7), and for $A_d$ is the result of experimental data approximation (table 4.) with a high degree of reliability ($R^2=0.9787$)

| Table 4. Dependence of the parameter $A_d$ of the restored imprint on the macrohardness. |
|-----------------------------------------------|
| Material | Cu | Fe | HS 18-0-1 ann. | HS 18-0-1 quen.+temp. | VK6 |
| $HV_{\text{macro}}$, kg mm$^{-2}$ | 93 | 86 | 236 | 747 | 1490 |
| $A_d$ | 4.068 | 3.295 | 2.268 | 1.334 | 0.875 |

Dependencies $A_D$ and $A_d$ on macro-hardness – hyperbolic (figure 4) and are described by the equations:

$$A_D = 43.05 \ (HV_{\text{macro}})^{-0.5}$$

(8)

$$A_d = 34.34 \ (HV_{\text{macro}})^{-0.497}$$

(9)

where $HV$ dimension is kg mm$^{-2}$.

Thus, in this paper there was for the first time established that in the microhardness range there is a correlation between the diagonal of the restored imprint and the material macrohardness Eqs. (5) and (9) corresponding. This dependency is first clause of the developed method that establishes a connection between macro and microhardness.

The revealed dependency between $HV_{\text{macro}}$ and material constant $A_d$ is not yet possible to establish a qualitative relationship between $HV_{\text{macro}}$ and $HV_{\text{micro}}$. To obtain it, it is necessary to determine the values of fractional exponent $z$ in the Eq. (5).
Figure 4. Dependency of $A_D$ and $A_d$ parameters non-recovered and recovered imprints on material macro-hardness: $A_D$ – dotted; line $A_d$ – solid line.

In this paper, a linear dependency is established (with extremely high reliability – $R^2=0.9958$), between the fractional exponent $z$ in Eq. (5) and the parameters $A_d$ and $A_D$ ratio (table 5, figure 5), depended on the sizes of diagonals of recovered and non-recovered imprints – Eq. (5) and (6) and thus, characterizing the value of elastic recovery:

$$z = -0.218 \frac{A_d}{A_D} + 0.712$$

Table 5. $A_D$, $A_d$ constants and fractional index $z$ relationship.

| Material                  | Cu  | Fe  | HS 18-0-1 ann. | HS 18-0-1 quen.+temp. | VK6 |
|---------------------------|-----|-----|----------------|------------------------|-----|
| $A_d/A_D$                 | 0.91| 0.71| 0.81           | 0.85                   | 0.78|
| $z$                       | 0.514| 0.558| 0.535          | 0.527                  | 0.540|

Figure 5. Dependence of the fractional exponent $z$ on the parameters $A_D$ and $A_d$.

The ratio $A_d/A_D$ depends on the size of the diagonals of the recovered and non-recovered imprints and, thus characterizes the value of elastic recovery:

The correctness of Eq. (10) is proved as follows: with $A_d=A_D$, i.e. when transiting from micro to macro range, the value of the fractional exponent $z$ is to be 0.5. Calculated with $A_d=A_D$ Eq. (10) value: $z=0.494$. The relative error is $-1.2\%$, which corresponds to round off error.

Linear dependency of the index $z$ in the Eq. (10) on the ratio $A_d$ and $A_D$ is the second concept of the developed method.

Eq. (10) is obtained by approximating dependencies $\langle P\cdot d \rangle$, where $P$ and $d$ – experimental data. Alongside this, there were established dependencies $A_D$ and $A_d$ on macrohardness: rigorous mathematical one for $A_D$ (Eq. (8)) and obtained by approximation for $A_d$ (Eq. (9)).
By substituting values \( A_d \) and \( A_z \) into the Eq. (10) as \( HV_{macro} \) function, we will obtain the fractional exponent \( z \) dependency directly on the microhardness:

\[
    z = -0.174HV_{macro}^{0.003} + 0.712
\]

(11)

The concept about the fractional exponent \( z \) linear dependency on the elastic deformation value (ratio \( A_d/A_d = \) Eq. 10), and also on material microhardness (\( HV_{macro} = \) Eq. 11) is very important and requires a special discussion.

1. In the paper [9], a linear interdependence between the yield strength (determining the value of elastic deformation) and the material hardness. This indicates the correctness of both Eqs. (10) and (11).

2. Correlation graphs of experimental dependencies \( «P - d» \) (see table 3) – formula 10 and \( «HV_{macro} - A_d, d» \) (figure 4 and table 4) – Eq. 11 are built up according to Ordinary Least Squares, herein \( R^2 \neq 1 \), i.e. they do not go through all the experimental points. It determines mismatching values of parameters \( A_d \) and \( z \), obtained by IM according to formulæ (8, 9, 10), and as a result of experimental data approximation (table 6).

Herein, the b differences in the diagonals values of the recovered imprints, obtained and calculated, are not great (table 7), in some cases are not higher than roundoff errors and practically correspond to measurement errors. The greatest difference in diagonal sizes \( - 0.001 \) mm, specified in ISO 6507-1: 2005 for small loads (0.096 H), occurs only twice (copper and iron, load 0.096 H – see table 7), with the relative error for these cases less than 10% (table 7).

**Table 6.** The values of the parameters \( A_d \) and \( z \) according to the experiment and IM.

| Material         | Parameters according to \( «P-D(d)» \) | Parameters according to IM |
|------------------|----------------------------------------|-----------------------------|
|                  | \( A_d \) | \( z \) | \( A_d \) | \( z \) |
| Cu               | 4.07     | 0.514  | 3.61     | 0.535  |
| Fe               | 3.29     | 0.56   | 3.75     | 0.536  |
| HS 18-0-1 ann.   | 2.27     | 0.535  | 2.28     | 0.535  |
| HS 18-0-1 quen.+temp. | 1.33 | 0.527  | 1.29     | 0.534  |
| VK6              | 0.88     | 0.540  | 0.91     | 0.534  |

**Table 7.** The restored imprint diagonal: experimental (according to \( «P-(D, d)» \)) and IM.

| P, g | \( d \) (μm) | \( P \) (μm) | Cu | Fe | HS 18-0-1 ann. | HS 18-0-1 quen.+temp. | VK6 |
|------|--------------|-------------|----|----|---------------|-----------------------|-----|
|      | Exp. | IM | Exp. | IM | Exp. | IM | Exp. | IM | Exp. | IM | Exp. | IM |
| 10   | 13.4 | 12.41 | (7.4) | 11.9 | 12.9 | (8.4) | 7.3 | 7.8 | (7.1) | 4.5 | 4.3 | (3.5) |
| 25   | 21.1 | 20.25 | (4.02) | 19.5 | 21.04 | (7.9) | 12.7 | 12.8 | (0.4) | 7.2 | 7.1 | (2.0) |
| 50   | 30.2 | 29.38 | (2.7) | 29.5 | 28.3 | (3.4) | 18.8 | 18.4 | (2.1) | 10.6 | 10.2 | (3.9) |
| 100  | 43.1 | 42.60 | (1.3) | 42.3 | 44.25 | (4.6) | 26.9 | 26.8 | (0.4) | 15.2 | 14.7 | (3.4) |
| 200  | 62.1 | 61.73 | (0.6) | 65.4 | 63.2 | (1.9) | 38.6 | 38.8 | (0.5) | 21.6 | 21.2 | (2.08) |

3. Eq. 11 analysis shows a very weak \( z \) dependence on \( HV_{macro} \). This is a consequence of the power index small value of the \( HV_{macro} \) value \( = -0.003 \). So, \( 90^{0.003} = 1.013, 1500^{0.003} = 1.022 \) (is shown for minimal and maximal roundoff materials hardness values accepted for the study) and due to the fact, that the elastic deformation magnitude for materials with significantly different hardness differs slightly.

To estimate the magnitude of elastic deformation \( \Delta \varepsilon_d \) work there was used \( «P-(D, d)» \) in the chart, was determined as:
— force value \( P \), transition from micro range into macro range (intersection (tangent) point of curves «P-D» and «P-d» on «P-(D, d)» diagram, fig 3.), by solving equation: \( A_D \cdot P^{0.5} = A_d \cdot P^Z \);

— total work of material deformation \( \varepsilon_{tot} \) (into elastic and plastic deformation) at the indenter embedding, solving certain integrals \( \int_{10}^{P_i} A_D P^{0.5} dP \);

— the work of plastic deformation \( \varepsilon_{pl} \), solving definite integrals \( \int_{10}^{P_i} A_d P^Z dP \);

— elastic deformation share: \( \Delta \varepsilon_{el.} = \frac{(\varepsilon_{tot} - \varepsilon_{pl})}{\varepsilon_{tot}} \).

Values \( \Delta \varepsilon_{el.} \) for materials with substantially different hardness are close, the difference does not exceed ~ 2% (table 8).

### Table 8. The elastic work magnitude of deformation \( \Delta \varepsilon_{el.} \) while indenting in micro range.

| Material       | Cu | Fe | HS 18-0-1 ann. | HS 18-0-1 quen.+temp. | VK6 |
|----------------|----|----|----------------|-----------------------|-----|
| \( \Delta \varepsilon_{el.} \), % | 3.4 | 3.5 | 1.2            | 1.8                   | 1.2 |

It should be noted that these data correspond well with the value of elongation (\( \delta \)) in tensile tests, \( \delta \) – a small value that is not even always taken into account on the deformation curves [10]: \( \delta \approx \frac{\sigma_{0.2}}{E} \),

where: \( \delta \) – max elastic relative elongation, \( \sigma_{0.2} \) – yield strength, \( E \) – elastic modulus. The value \( \delta \) is (approximately), %: Cu – 0.05 (\( \sigma_{0.2}=70 \) MPa, \( E=138 \) GPa [11]); Fe – 0.06 (\( \sigma_{0.2}=120 \) MPa, \( E=210 \) GPa [11]); HS 18-0-1 ann. – 0.39 (\( \sigma_{0.2}=850 \) MPa, \( E=220 \) GPa [12]); HS 18-0-1 quen. + temp. – 1.3 (\( \sigma_{0.2}=2900 \) MPa; \( E=220 \) GPa [12]).

Thus, our experimental data (table 7) proved the developed method correctness.

Its use allows solving the following tasks.

1) Estimate material \( H V_{micro} \) with any indentation load, if its \( H V_{macro} \) is known, performing the following calculations:

\( A_D \) on Eq. (8); \( A_d \) on Eq. (9); \( d \) on Eq. (10); \( d \) the recovered imprint diagonal on Eq. (5) thus, Vickers microhardness, for any \( P \) values.

2) Calculate material \( H V_{micro} \) with any indentation load, and \( H V_{macro} \), if even one parameter for \( H V_{micro} \) and \( P \) load with which microhardness was determined are known (these very data are often cited in the literature).

3) Estimating \( H V_{macro} \) the following calculations are performed:

\( z \) (Eq. 11), having accepted \( H V \), equal to \( H V_{micro} \) instead of \( H V_{macro} \) in this case, the error will be insignificant due to the small value of the fractional exponent; \( A_d \) (Eq. 5); \( H V_{macro} \) (Eq. 9).

4) Calculating \( H V_{micro} \):

calculating \( z \) (Eq. 11), using as well value \( H V_{micro} \); calculating \( A_d \) (Eq. 9); calculating \( d \) – recovered imprint diagonal (Eq. 5.) and thus Vickers micro-hardness for any \( P \) values.

The method verification was performed using literature data, considering that the obtained positive result on our own experimental data (table 7.) requires additional confirmation. Calculations were performed for works in which data are given and upon \( H V_{micro} \), and upon \( H V_{macro} \). This made possible to compare the experimental data and the results of the calculations performed by the developed «the imprint method».

\( H V_{micro} \) estimating according to the known value of \( H V_{macro} \) was performed for gallium antimonide (GaSb), for which data on macro and microhardness are presented in the paper [1].

With hardness 400\( H V \): \( A_D=2.15 \) (Eq. 8); \( A_d=1.748 \) (Eq. 9); \( z=0.535 \) (Eq. 10).

The results of the estimating micro-hardness with various indentation efforts should be considered to be satisfactory. Maximum relative error \( d \sim 5\% \), while the absolute difference between experimental and calculated \( d \) for all loads less than 0.001 mm (table 9).

Defining \( H V_{macro} \) and \( H V_{micro} \) with the certain \( H V_{micro} \) value at a certain load was performed for Germanium (Ge), for which data on macro-and microhardness are given in the work [1].
The method also tested when calculating macro-hardness using literature data [13], in which the values of micro-hardness are given only under one specific load and macro-hardness (table 11).

Table 11. Macro-hardness calculation by one micro-hardness value.

| Material | $HV_{micro}$ | Load, g | $d$, µm | Method parameters | $HV_{macro}$, A | $HV_{macro}$, B | $Δ$, % |
|----------|--------------|---------|---------|------------------|----------------|----------------|-------|
| WC       | 1780         | 30      | 5.5     | 0.5335, 0.9      | 1620           | 1520           | 6.1   |
| UC       | 923          | 50      | 10.0    | 0.5320, 1.25    | 700            | 785            | 12.1  |
| Cr2Si    | 1050         | 50      | 9.4     | 0.5325, 1.13    | 960            | 962            | 0.2   |
| Ta2Si    | 1407         | 50      | 8.1     | 0.5337, 1.004   | 1100           | 1220           | 10.9  |

Notes. In columns “A” – data [12]; in columns “B” – calculated $HV_{macro}$ values by IM.

The results obtained in the analysis of the literature data (see tables 9-11) confirm the reliability and sufficiently high, at least, satisfactory accuracy of the developed method.

4. Conclusions.

The method “method of prints” was developed, which establishes an analytical relationship between micro- and macro-hardness. The method is based on the analysis of the recovered and non-recovered imprint diagonals values in indenting by Vikers method.

The method allows analytically determine:

1) micro-hardness at various loads by the macro-hardness of the material without additional measurements;

2) macro-hardness and micro-hardness at different loads of the material by one measurement of macro-hardness.

A correlation was established between the diagonal of the recovered imprint in the micro-hardness area and the macro-hardness of the material.
The imprints method is tested for materials with different hardness when solving direct (micro-hardness determination by macro-hardness value) and vise versa. A good coordination was obtained between literature data and calculation results.

The developed method of imprints provides high reliability of the results, confirmed by the analysis of experimental and literature data and satisfactory accuracy of determining macro and microhardness with a relative error of no more than 10% in a wide range of hardness values studied (80…1500 HV) and for different load in micro range.

The method will allow systematizing the data on micro- and macro-hardness for various materials given in the scientific and reference literature.

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