Calculation of Correction Factors for Vickers' Hardness Measurements on a Non-Planar Surface

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Received 11.05.2022
Accepted for publication 21.07.2022

Abstract

The exact determination of Vickers HV hardness is important for determining of the product material mechanical properties. An important aspect of measuring HV is to obtain its values on a non-planar surface. Regulatory documents contain table values of correction factors *K* which depend on the surface shape (convex or concave, spherical or cylindrical), its curvature (diameter *D*) and hardness (arithmetic mean *d* of indentation diagonal lengths) but this does not solved the problem. The *K* values for *d*/*D* ratios not given in the tables are determined by interpolation from the closest to the measured tabulated *d*/*D* values. The error in the representation of these tabulated *d*/*D* values is fully included in the error of determining the *K* coefficient for the measured *d*/*D* ratio. The aim of the work was to simplify the calculation of correction factors *K* for Vickers hardness measurements on non-planar surfaces and to reduce the calculation error compared to the methodology governed by the regulations.

The method presented is based on a statistical analysis of *K* coefficients, presented in regulatory documents for cases considered in the form of tables. The sufficiency of using of a quadratic power function for approximating *K*(*d*/*D*) dependences and the necessity of fulfilling the physically justified condition $K \equiv 1$ at zero curvature of tested surface have been substantiated. Simplification of calculation of *K* coefficient and decrease of calculation error in comparison with the recommended in the regulatory documents obtaining of *K* value by linear interpolation relative to two adjacent table values are shown.

The reduction of the calculation error in comparison with the calculation recommended in the regulatory documents occurred because of the reason that when calculating by the developed formulas, the error in the value of the calculated for a specific value of *d*/*D* coefficient *K* is averaged over all n values of *d*/*D* given in the table of GOST for a given surface. That is, the error is reduced by a factor of about $\sqrt{n/2}$ in comparison with the calculation according to the regulated procedure. This is illustrated by the above numerical data and an example of the use of the method.

The obtained formulas for calculation of correction coefficients *K* when measuring hardness HV on spherical and cylindrical (concave and convex) surfaces are reasonable to use for automatic calculation of HV on items with a non-planar surface.

Keywords: hardness measurements, Vickers method, concave and convex surfaces, correction factors.

DOI: 10.21122/2220-9506-2022-13-3-189-198

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Для цитирования:
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Расчёт поправочных коэффициентов при измерении твёрдости по Виккерсу на неплоской поверхности

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Поступила 11.05.2022
Принята к печати 21.07.2022

Точное определение твёрдости HV по Виккерсу важно для определения механических свойств материала изделий. Важным аспектом измерения HV является получение её значений на неплоской поверхности. Включение в нормативные документы табличных значений поправочных коэффициентов *K*, зависящих от формы (выпуклая или вогнутая, сферическая или цилиндрическая) поверхности, её кривизны (диаметра *D*) и твёрдости (среднего арифметического *d* длин диагоналей отпечатка) не решает проблему. Значения *K* для отношений d/D, не приведённых в таблицах, определяют интерполяцией от ближайших к измеренному табличных значений d/D. Погрешность представления этих табличных значений d/D полностью включается в погрешность определения искомого коэффициента *K* для измеренного отношения d/D. Цель работы – упрощение расчёта поправочных коэффициентов *K* при измерении твёрдости по Виккерсу на неплоских поверхностях и снижение погрешности расчёта по сравнению с методикой, регламентированной нормативными документами.

Разработка основана на статистическом анализе коэффициентов *K*, представленных в нормативных документах для рассмотренных случаев в виде таблиц. Обоснована достаточность использования квадратичной степенной функции для аппроксимации зависимостей $K(d/D)$ и необходимость выполнения физически обоснованного условия $K \equiv 1$ при нулевой кривизне испытуемой поверхности. Показано упрощение расчёта коэффициента *K* и снижение погрешности расчёта по сравнению с рекомендованным в нормативных документах получением значения *K* линейной интерполяцией относительно двух соседних табличных значений.

Снижение погрешности расчёта по сравнению с расчётом, рекомендованным в нормативных документах, происходит за счёт того, что при расчёте по разработанным формулам погрешность в значении рассчитанного для конкретного значения d/D коэффициента *K* усредняется по всем *n* значениям d/D, приведённым в таблице ГОСТа для данной поверхности. То есть снижается примерно в $\sqrt{n/2}$ раз по сравнению с расчётом по регламентированной методике. Это иллюстрируют приведённые численные данные и пример использования методики.

Полученные формулы для расчёта поправочных коэффициентов *K* при измерении твёрдости HV на сферических и цилиндрических (вогнутых и выпуклых) поверхностях целесообразно использовать для автоматического расчёта HV на изделиях с неплоской поверхностью.

Ключевые слова: измерения твёрдости, метод Виккерса, вогнутые и выпуклые поверхности, поправочные коэффициенты.

DOI: 10.21122/2220-9506-2022-13-3-189-198

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Introduction

Hardness measurement is one of the main methods for assessing of strength characteristics of metals [1–3]. An indentor of a specified shape is pressed into the surface under test with a specified load for a specified time. After the load is removed from the indentor, an indentation remains on the surface and the area of the indentation is determined. The ratio of the indenting load to the area of the indentation is the hardness value. Because of their speed and ease of measurement, hardness values are widely used in metallurgical examinations.

The hardness of small thickness parts and surface layers is determined by Vickers (HV) [4, 5] – by pressing a four-sided diamond pyramid into the ground metal surface and determining the hardness HV by the formula:

$$\mathrm{HV} = \frac{2P\sin(\alpha/2)}{d^2} \approx 1.854\frac{P}{d^2}, \tag{1}$$

where P is load on the pyramid; $\alpha = 136^\circ$ is angle between opposite sides of the pyramid at the top; d, mm is arithmetic mean of the lengths of the print diagonals measured after the load is removed (the difference of the print diagonals should not exceed 2 % of the smaller of them).

In accordance with [5], depending on the applied load P, the following terms are used:

– for a load of 49.03 N or higher is the term “Vickers hardness” and the range of hardness scales is designated “HV ≥ 5”;

– 1.961 to 49.03 N is the term “low load hardness”; the hardness scales is labeled “0.2 ≤ HV < 5”;

– for loads between 0.09807 and 1.961 N is the term “microhardness” and the range of hardness scales denote “0.01 ≤ HV < 0.2”.

These criteria are formal and have no physical substantiation [6].

The method of microhardness or hardness with small load is the only method that allows to determine the hardness of phases and structural components of multicomponent alloys. It is established that in the range of microhardness there is an “Indentation Size Effect” [7]. It manifests itself in the fact that hardness values determined after removing the indenter from the test specimen, the higher the lower the load. Attempts to establish an analytical dependence of microhardness on load and to relate micro- and macrohardness have not been successful. It was shown in [8] that the dimensional effect is related to the fact that the elastic deformation of the material, which develops during indenter penetration and disappears after its removal, is not taken into account in hardness estimation. In contrast, in the macrohardness range, hardness values are load-independent due to the small fraction of elastic deformation.

The importance of accurate determination of HV hardness by Vickers is also due to the fact that its use (“in some particular cases” [4]) is recommended in determining the mechanical properties of the product material [6, 9, 10] and their distribution in the product [11].

Another important aspect of measuring the Vickers HV hardness is to obtain its values on a non-planar surface of products. This problem has been solved by including in normative documents [4, 5] correction factors K depending on the shape (convex or concave, spherical or cylindrical) of the surface, its curvature (diameter D) and hardness (arithmetic mean d of the indentation diagonals). In [4, 5] the values of K-factors are given in tabular form (the data [4] and [5] coincide, except for a misprint in [4] in the value $d/D = 0.079$ for the spherical convex surfaces). The K coefficient values given in [4, 5] from the value of 0.995 or 1.005 with a discreteness of 0.005 correspond to the values (accurate to the third decimal place) of the ratio d/D. The K values corresponding to the d/D ratio ratios not given in the d/D ratio tables in [5, Appendix B] propose to determine (examples are given for spherical and cylindrical surfaces) by “interpolation” of the K coefficient values given in the corresponding tables for the d/D ratio values closest to the measured one.

The regulated in [5] method of determining the correction coefficients K, taking into account the shape and curvature of the non-planar surface of the measured product, is not convenient to use and is not accurate enough. According to it, to determine the value of correction coefficient K for the ratio d/D obtained as a result of measurement, the closest tabular values of d/D ratio are used, the accuracy of representation of which is limited to the third decimal place after the decimal point. The error in represen-ting these “closest” d/D ratio values is completely included in the error in determining the desired correction factor K for the measured d/D ratio. This reduces the achievable accuracy of the Vickers HV hardness measurement method for products with curved surfaces, including the hardness of thin films applied to them [12].

The aim of the work was to simplify the calculation of correction factors K for Vickers hardness measurements on non-planar surfaces and to reduce the calculation error compared to the methodology governed by the regulations.

Development of the required analytical expressions

Let us use the data on the relationships between the values of the correction factor K and the values of the ratio d/D for surfaces of different shapes and curvatures given in [5, Tables B.1–B.6]. These data are grouped in Tables 1–3.

Table 1

Correction factors *K* for spherical surfaces

Convex surfaces			Concave surfaces		
d/D	Correction factor K		d/D	Correction factor K	
	According to [5]	Calculation of the (2)		According to [5]	Calculation of the (3)
0.004	0.995	0.99395	0.004	1.005	1.00454
0.009	0.990	0.99039	0.008	1.010	1.00924
0.013	0.985	0.98621	0.012	1.015	1.01410
0.018	0.980	0.98107	0.016	1.020	1.01913
0.023	0.975	0.97601	0.020	1.025	1.02431
0.028	0.970	0.97104	0.024	1.030	1.02967
0.033	0.965	0.96617	0.028	1.035	1.03518
0.038	0.960	0.96138	0.031	1.040	1.03942
0.043	0.955	0.95667	0.035	1.045	1.04522
0.049	0.950	0.95115	0.038	1.050	1.04968
0.055	0.945	0.94575	0.041	1.055	1.05423
0.061	0.940	0.94049	0.045	1.060	1.06044
0.067	0.935	0.93534	0.048	1.065	1.06520
0.073	0.930	0.93033	0.051	1.070	1.07006
0.079	0.925	0.92544	0.054	1.075	1.07500
0.086	0.920	0.91991	0.057	1.080	1.08004
0.093	0.915	0.91454	0.060	1.085	1.08517
0.100	0.910	0.90935	0.063	1.090	1.09039
0.107	0.905	0.90433	0.066	1.095	1.09571
0.114	0.900	0.89949	0.069	1.100	1.10111
0.122	0.895	0.89416	0.071	1.105	1.10477
0.130	0.890	0.88907	0.074	1.110	1.11032
0.139	0.885	0.88361	0.077	1.115	1.11597
0.147	0.880	0.87899	0.079	1.120	1.11979
0.156	0.875	0.87407	0.082	1.125	1.12559
0.165	0.870	0.86944	0.084	1.130	1.12951
0.175	0.865	0.86463	0.087	1.135	1.13547
0.185	0.860	0.86017	0.089	1.140	1.13949
0.195	0.855	0.85607	0.091	1.145	1.14355
0.206	0.850	0.85197	0.094	1.150	1.14972

Table 2

Correction factors *K* for concave cylindrical surfaces

Correction factor *К* according to [5]	The diagonals are rotated 45º about the axis		One of the diagonals is parallel to the axis	
	d/D according to [5]	Calculation K of the (4)	d/D according to [5]	Calculation K of the (5)
1.005	0.009	1.00522	0.008	1.00365
1.010	0.017	1.00992	0.016	1.00808
1.015	0.025	1.01468	0.023	1.01261
1.020	0.034	1.02009	0.030	1.01774
1.025	0.042	1.02497	0.036	1.02262
1.030	0.050	1.02991	0.042	1.02794
1.035	0.058	1.03490	0.048	1.03371
1.040	0.066	1.03995	0.053	1.03885
1.045	0.074	1.04505	0.058	1.04430
1.050	0.082	1.05021	0.063	1.05006
1.055	0.089	1.05478	0.067	1.05489
1.060	0.097	1.06005	0.071	1.05991
1.065	0.104	1.06470	0.076	1.06647
1.070	0.112	1.07008	0.079	1.07056
1.075	0.119	1.07483	0.083	1.07617
1.080	0.127	1.08031	0.087	1.08199
1.085	0.134	1.08515	0.090	1.08648
1.090	0.141	1.09004	0.093	1.09108
1.095	0.148	1.09497	0.097	1.09738
1.100	0.155	1.09995	0.100	1.10224
1.105	0.162	1.10496	0.103	1.10721
1.110	0.169	1.11003	0.105	1.11059
1.115	0.176	1.11513	0.108	1.11574
1.120	0.183	1.12028	0.111	1.12101
1.125	0.189	1.12473	0.113	1.12458
1.130	0.196	1.12996	0.116	1.13003
1.135	0.203	1.13523	0.118	1.13372
1.140	0.209	1.13978	0.120	1.13747
1.145	0.216	1.14514	0.123	1.14318
1.150	0.222	1.14976	0.125	1.14705

Table 3

Correction factors *K* for convex cylindrical surfaces

Correction factor *K* according to [5]	The diagonals are rotated 45º about the axis		One of the diagonals is parallel to the axis	
	d/*D* according to [5]	Calculation *K* of the (6)	*d*/*D* according to [5]	Calculation *K* of the (7)
0.995	0.009	0.99481	0.009	0.9956
0.990	0.017	0.99024	0.019	0.99091
0.985	0.026	0.98513	0.029	0.98644
0.980	0.035	0.98007	0.041	0.98135
0.975	0.044	0.97506	0.054	0.97618
0.970	0.053	0.97009	0.068	0.97101
0.965	0.062	0.96516	0.085	0.96529
0.960	0.071	0.96027	0.104	0.95963
0.955	0.081	0.95490	0.126	0.95403
0.950	**0.090**	**0.95010**	0.153	0.94855
0.945	**0.100**	**0.94483**	0.189	0.94366
0.940	**0.109**	**0.94013**	0.243	0.94147
0.935	0.119	0.93496		
0.930	0.129	0.92985		
0.925	0.139	0.92478		
0.920	0.149	0.91978		
0.915	0.159	0.91482		
0.910	0.169	0.90993		
0.905	**0.179**	**0.90508**		
0.900	**0.189**	**0.90029**		
0.895	**0.200**	**0.89508**		

Correlation fields between the values of correction factors *K* and ratios *d*/*D* for surfaces of different shapes and curvatures are shown in Figures 1–3. The "Microsoft Excel" program and numerical values of *K* and *d*/*D* given in Tables 1–3 respectively were used for their construction. Statistical processing of correlation dependencies between *K* and *d*/*D* shown in Figures 1–3, construction of trend lines (polynomials of the second degree) of these dependencies and calculation of reliability of approximation R^2 (square of *R* correlation coefficient) was performed in the "Microsoft Excel" program. It should be noted that trend lines, equations of which are shown in Figures 1–3, are forcibly (programmatically) drawn through physically correct value of $K \equiv 1$ at zero curvature of tested surface (at $d/D = 0$).

Analysis of the results obtained

The following equations for determining the correction factors *K* for HV Vickers hardness measurements from the results of *d*/*D* ratios in the cases considered (sequentially for the dependencies shown in Figures 1*a*, 1*b*, 2*a*, 2*b*, 3*a*, 3*b*) were obtained:

$$K = 1.7729(l/D)^2 - 1.0838(l/D) + 1; \tag{2}$$

$$K = 5.0954(l/D)^2 + 1.1138(l/D) + 1; \tag{3}$$

$$K = 0.4446(l/D)^2 + 0.5759(l/D) + 1; \tag{4}$$

$$K = 6.1573(l/D)^2 + 0.4067(l/D) + 1; \tag{5}$$

$$K = 0.2711(l/D)^2 - 0.5788(l/D) + 1; \tag{6}$$

$$K = 1.0598(l/D)^2 - 0.4984(l/D) + 1. \tag{7}$$

The results of calculating the K coefficients according to the developed formulas (2)–(7) for the d/D values given in Tables 1–3 are given in these tables for the considered cases of the surface shape.

Information on the equations for calculating the correction coefficients K for HV Vickers hardness measurements on a non-planar surface in the cases considered are summarized in Table 4. The results of their statistical processing are also presented there: the reliability of R^2 approximation and the average values δ of the relative deviation module between the results of K_i coefficient K calculation by the developed formulas (2)–(7) and their tabulated (according to [5]) K_i(tabl) values for the curved surfaces under consideration.

The values of δ are calculated by the formula:

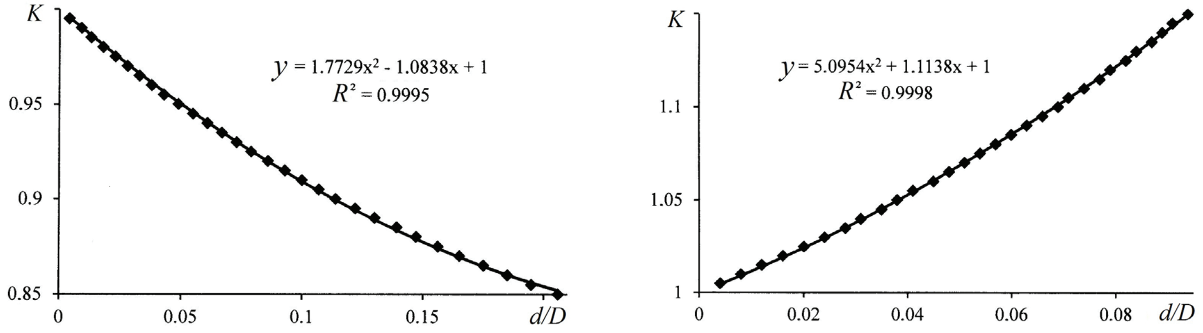
$$\delta = \frac{100\%}{n}\sum_{i=1}^{n}\frac{|K_i - K_i(\text{tabl})|}{K_i(\text{tabl})}, \tag{8}$$

where n is the number of values of the coefficient K in the corresponding columns of Tables 1–3.

Table 4

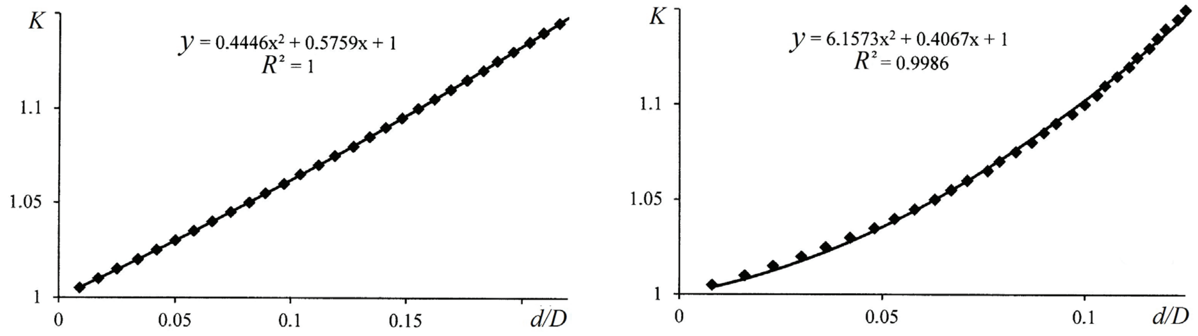
Information on equations for calculating *K*-correction factors for HV Vickers hardness measurements on a non-planar surface

Surface form	Indenter location	Table No, Figure No	Calculation formula	R^2	δ, %
Spherical, convex	Randomly	Table 1, Figure 1*a*	(2)	0.9995	0.0907
Spherical, concave		Table 1, Figure 1*b*	(3)	0.9998	0.0456
Cylindrical, convex	The diagonals are rotated 45° about the axis	Table 3, Figure 3*a*	(4)	1.0000	0.0153
Cylindrical, concave		Table 2, Figure 2*a*	(5)	1.0000	0.0132
Cylindrical, convex	One of the diagonals is parallel to the axis	Table 3, Figure 3*b*	(6)	0.9959	0.1069
Cylindrical, concave		Table 2, Figure 2*b*	(7)	0.9986	0.1293



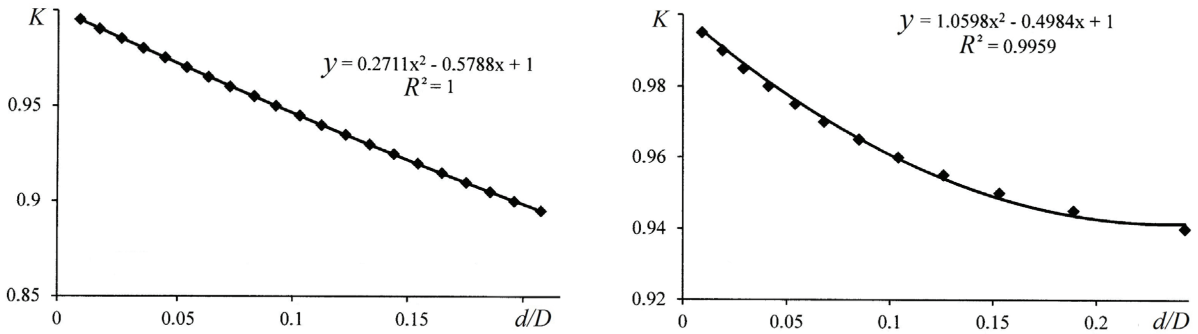
a *b*

Figure 1 – Dependence of correction coefficient K when measuring hardness HV by Vickers on convex (*a*) and concave (*b*) spherical surfaces on the ratio d/D of arithmetic mean d of indentation diagonal lengths to surface diameter D. Table data (points) according to Table 1 (Table B.1 (*a*) and Table B.2 (*b*) in [5]), their interpolating power trend line passing through the value $K = 1$ at $d/D = 0$, its equation and reliability of R^2 approximation



a *b*

Figure 2 – Dependence of the correction factor *K* when measuring HV hardness according to Vickers on a concave cylindrical surface when one of the diagonals of the indentation is oriented at an angle of 45° (*a*) and parallel (*b*) to the cylinder axis on the ratio *d*/*D*. Table data (points) according to Table 2 (Table B.4 (*a*) and Table B.6 (*b*) in [5]), their interpolating power trend line passing through the value $K = 1$ at $d/D = 0$, its equation and reliability of R^2 approximation



a *b*

Figure 3 – Dependence of the correction factor *K* when measuring HV hardness on a convex cylindrical surface with one of the indentation diagonals oriented at an angle of 45° (*a*) and parallel (*b*) to the cylinder axis on the ratio *d*/*D*. Table data (points) according to Table 3 (Table B.3 (*a*) and Table B.5 (*b*) in [5]), their interpolating power trend line passing through the value $K = 1$ at $d/D = 0$, its equation and reliability of R^2 approximation

The analysis of the results of statistical pro-ces-sing of calculations of correction coefficients *K* when measuring HV hardness by Vickers on a non-planar surface presented in Table 4 showed that the quadratic power functions (2)–(7) provide close to "1" reliability of approximation of the tabulated data [5] about the value *K* and not significant numerical deviations in their calculations. These deviations do not exceed the units of the lowest digit of the tabulated data [5] (see Tables 1–3) and are more accurate than the tabulated data, because they have less discreteness and better monotonicity (it is clearly seen, for example, for *d*/*D* values, highlighted in Table 3 in bold type) of *K*(*d*/*D*) dependences. In this connection, approximation of the experimental data by polynomials of higher powers or by functions of another kind does not make sense.

The calculation error is reduced in comparison with the calculation recommended in the normative documents due to the fact that the *K* coefficient value calculated according to the standard method includes the errors of the *K* coefficient representation for two neighboring points of surface curvature in Tables [5] due to the discreteness of their representation. When calculating by the developed formulas (2)–(7), the error in the value of the *K* coefficient calculated for a particular value of surface curvature is averaged over all n values given in the tables [5] for this type of surface. That is, the error is reduced by a factor of about $\sqrt{n/2}$ as compared with the calculation by the method [5]. This increases the accuracy of the Vickers HV hardness measurement method for products with curved surfaces. This is illustrated by the numerical data in Tables 1–3 and the following example of using the method of calculating correction factors.

The application of the formulas (2)–(7) to calculate the correction factors *K* in measuring the Vickers HV hardness on a non-planar surface is illustrated by their definition for a convex cylindrical surface of a wire 0.5 mm in diameter, on which a hardening coating is applied. Suppose the HV Vickers hardness measurements [5] on two parts of the wire yielded average values of diagonals (diagonals are turned 45° relative to the wire axis) of 0.0535 mm and 0.0585 mm, which correspond to *d*/*D* values of 0.107 and 0.117 respectively. By formula (6) we easily determine the values of correction factors *K*: they are equal to 0.94117 and 0.93599 accordingly. In determining the correction factors *K* by the standard procedure it would have been necessary to use the values 0.100 and 0.109; 0.109 and 0.119, the corresponding values of the correction factors 0.945 and 0.940; 0.940 and 0.935 (Table 3), to make the corresponding interpolations, and to determine the unknown values of *K*. The calculation result would have included the errors due to the discrepancy between the tabulated *d*/*D* and *K* values.

Thus, when determining the value of the correction factor *K* for the measured *d*/*D* ratio, which does not coincide with the tabulated values, the calculation according to the developed formulas provided a result more simple and accurate than the methodology regulated in [5].

Conclusion

Statistical analysis of correction coefficients *K* in measuring HV hardness according to Vickers on spherical and cylindrical (concave and convex) surfaces presented in normative documents in the form of tables has given analytical expressions for calculating *K* in all analyzed cases. The sufficiency of use of the quadratic power function for approximation of the obtained dependences and the necessity of fulfilling the physically justified condition $K \equiv 1$ at zero curvature of the tested surface have been substantiated. The simplification is shown and the decrease in the error of calculating the *K* coefficients according to the developed formulas is substantiated in comparison with the obtained *K* value by interpolation with respect to two neighboring table values recommended in the normative documents. It is reasonable to use the obtained expressions for automatic calculation of HV hardness according to Vickers on articles with a non-planar surface.

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