HARDNESS STANDARD EQUIPMENT

1989

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PREFACE

What is the usual procedure if one wants to start activity in a new metrological field ?

The first step is a study of the available literature. However, the representativeness of the literature of which one is aware is always questionable, even if a specialized agency (library) has been commissioned to search for it. Many articles which seem to be useful on the basis of their title or summary do not contain information on the specific subject of interest and others may be missed.

The next step is to visit other laboratories. Knowledge is thus enlarged, but perhaps in a single direction, that of the equipment in the laboratory visited. Such visits also give an opportunity to acquire additional literature references.

In studying the literature the language problem represents a huge obstacle. English texts are accessible practically all over the world, but other languages, even those spoken by great nations, may be less commonly available or understood. Languages written in non-Roman characters may present additional problems. The translation of specialized technical texts in languages confined to small populations may be an obstacle difficult to surmount in most countries; and these languages are often used for valuable publications; e.g. the literature on the metrology of hardness testing in Czech, Hungarian or Polish is very rich.

The above reasons are sufficient justification for literature surveys, in which the publications in a limited field are classified and the essential statements or data are reproduced in an easily accessible manner.

The present volume tries to perform this service in the field of hardness standard equipment. Many solutions are described. A few of these are no longer used, or perhaps have design features that are not completely mature. Even these should not be forgotten. The history of technology shows many examples of ideas being taken up again after a period of lying fallow.

The present publication continues the OIML series for restricted distribution on hardness measurement, namely :

The metrology of hardness scales. Bibliography, 1981,
Factors influencing hardness measurement, 1983,
Hardness test blocks and indenters, 1984.

The system of numbering of references employed here is identical with that in the above-mentioned Bibliography.

An attemp is made to collate the research results from a narrow section of the field of hardness measurement, and to make them available in a more-or-less unified presentation. The reader can always study the original publications in more detail, if necessary.

The wealth of literature published continuously is a healthy sign of the interest in and importance of the subject.

The author wishes to express his appreciation to the research workers listed in the Index, whose results were summarized. Any comments, proposals or additions to the text or to the references will be welcomed and appreciated.

Dr Ferenc PETIK
Assistant Director

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PART I. DESIGN

1. The hardness standardizing machine

1.1. Possibilities of improving the metrological characteristics of commercial hardness testers

A standardizing machine should have much better uncertainty values than hardness testers in current use. To see the possible ways of reducing uncertainty of hardness testing machines, the working principle of commercial hardness testers should be examined first.

The principle of a Rockwell hardness tester is shown in Fig. 1. Test piece W is arranged on a table which can be raised and pressed against indenter S by the help of a spindle. Load is transmitted to the indenter by weights G, by means of lever B, which can be arrested or freed by cam C. Penetration depth is measured by dial gauge M actuated by transmission lever H.

To analyse error sources and their possible elimination, let us examine them one after another, discussing in parallel commercial hardness testers and standardizing machines.

Commercial hardness tester

Loading : Fig.2 [W-13] shows the loading elements in initial position (I, drawn in thin lines) and after having applied the load (II) (the drawing exaggerates actual displacements).

The frame of the tester is deformed at load application, consequently the support of knife edge 0 is displaced in two directions. The result is an inclination α of the indenter with respect to the vertical. Knife edges of the lever at O, S, and G are sources of friction.

Load application : Speed of penetration on a commercial hardness tester is controlled mostly by a hydraulic dash-pot.

Standardizing machine

These deficiencies can be eliminated by direct dead-weight loading according to Fig. 3, and by a closed symmetrical, rigid machine frame as shown in Fig. 4. Weights in Fig. 3 are arranged above the indenter. The first experimental hardness standardizing machine was actually of this arrangement, but it was soon modified to the solution generally employed now which will be shown later (Fig. 6),i.e. weights hanging below the point of the indenter.

On standardizing machine dash-pots are controlled precisely. Indenter speed is checked periodically by a stop-watch, or other devices are built in which ensure a reproducible indentation process.

Indenters :

Indenters used with standardizing machines have reduced geometrical tolerance limits and better surface quality (see OIML Publication "Hardness test blocks and indenters"). Further the checking of indenters is improved with respect to commercial hardness testers.

Specimen support : The spindle raising the specimen supporting table of a commercial hardness tester may be the source of small displacements due to oil films, clearances or excentric mounting.

On standardizing machines the specimen, i.e. the hardness test block is arranged on a rigid work table forming part of the machine frame. Since lateral forces are not exerted by the indenter, due to suitable design, it is sufficient to lock the block only in vertical direction.

Depth measurement : The lever actuated dial gauge employed for indentation depth measurement on commercial Rockwell hardness testers may be the source of considerable errors, such as changing transmission ratio of the lever, hysteresis and inaccuracies in the dial gauge etc. One should recall that 1 HRC corresponds to 2 µm indentation depth. Hardness values used to be given in industrial practice in tenths of a HRC unit, i.e. in tenths of a micrometer. This fact shows that the possibilities of the dial gauge are exploited to the utmost, no improvement is expectable with the classical design.

On Rockwell standardizing machines the displacement of the indenter or of coaxial component parts is measured directly (Abbe's principle) (Fig. 5). The measuring microscopes, the electrical length measuring devices, or automatic laser interferometers used on standardizing machines lately permit to determine indentation depth with the required precision and accuracy.

Vickers and Brinell indentations produced on a standardizing machine are measured in general on measuring microscopes which do not form an integral part of the machine itself.

1.2. General arrangement of standardizing machines

Force steps of hardness standardizing machines are produced by discrete weight pieces. As forces necessary for various hardness testing methods are different, in general separate standardizing machines are built for the different testing methods, such as :

- Rockwell,
- Rockwell Superficial,
- Vickers,
- Brinell

The first two methods differ from the others by employing a

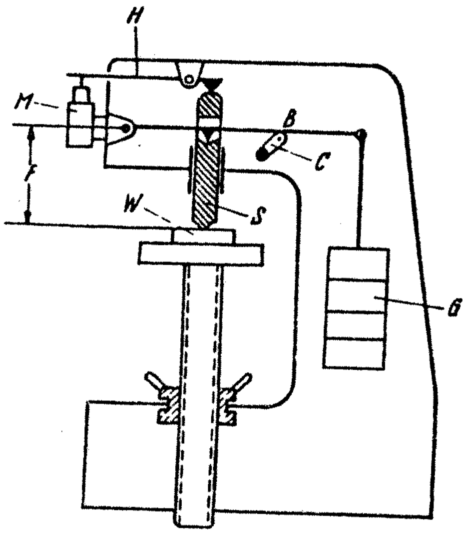


Fig. 1. The principle of a Rockwell hardness tester

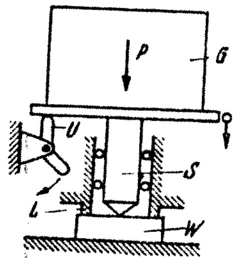


Fig. 3. Dead weight loading for hardness testing

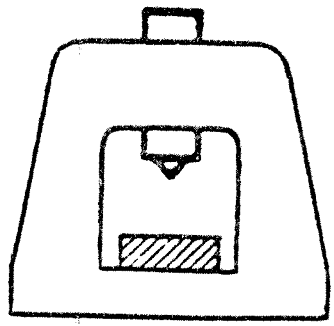


Fig. 4. Closed symmetrical machine frame for standardizing machines

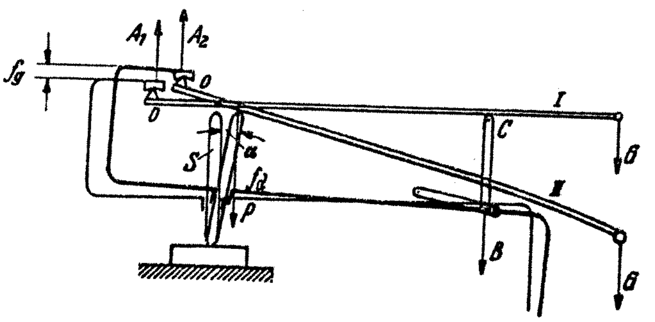


Fig. 2. Displacement of some elements of the Rockwell tester at load application

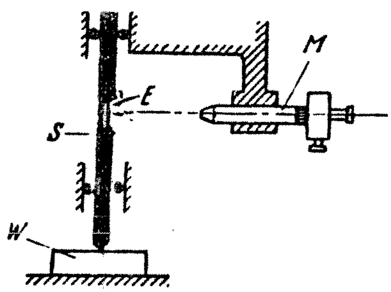


Fig. 5. Measurement of indentation depth on the shaft of the indenter (Abbé's comparator principle)

preliminary force, which is however not identical for the two Rockwell methods (98.07 and 29.42 N, i.e. 10 and 3 kgf, respectively), necessitating two separate machines. Vickers and Brinell standardizing machines (the latter up to a force of 1839 N, or 187.5 kgf) are often united to a single unit. The frequently employed Brinell test force of 29.42 kN (3000 kgf), however, necessitates a separate, more sturdy standardizing machine.

The principle of a dead-weight Rockwell standardizing machine is shown in Fig. 6. This design is employed in most institutes with slight modifications, as it will be shown later. On account of the necessity of a preliminary force at Rockwell tests, the loading equipment is more complicated in the case of the Rockwell method, than for the other two methods.

The test block is clamped on the rigid worktable C, which forms a part of the machine frame shown in black in Fig. 6 (b). Indenter E can move vertically in the center line of the machine. By means of coil spring F a load frame H is connected to the indenter. The mass of this frame, of the indenter and of the plunger carrying the indenter represent the preliminary force. These are shown in black in Fig. 6 (c). Another frame (K), together with weights arranged on it, represent the additional force. (The elements ensuring the total test force are shown in Fig. 6 [d]).

The loading mechanism is actuated by hydraulic ram I. In the position shown in Fig. 6 the ram supports both frames. This is the position before the test, prior to the application of the preliminary force. If the ram is made to sink, first the upper frame will be hanging freely, supported only by the indenter, hereafter the lower frame and the weights will be hanged on the upper frame, smooth transition and elastic contact being ensured by a coil spring.

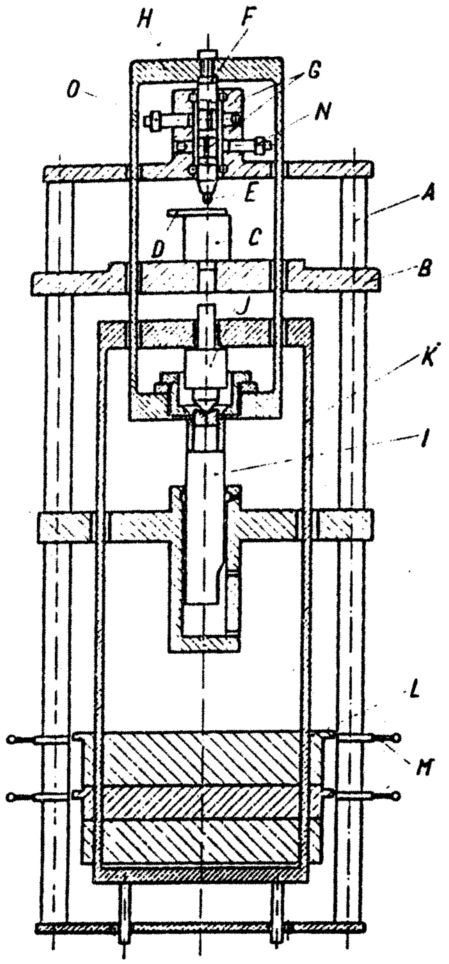
In the lowest position of the ram both frames hang freely on the indenter, this is the application of the total force. If the ram is made to rise again, first frame K, afterwards frame H is raised, thus the indenter is removed from the block.

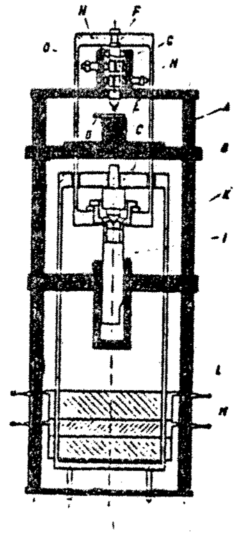
Brinell and Vickers standardizing machines have only a single loading frame and the hydraulic ram has only two positions.

Indentation depth at Rockwell tests is measured by measuring microscopes O and N fixed to the frame with their axis perpendicular to that of the plunger carrying the indenter. Scales G are attached to the plunger.

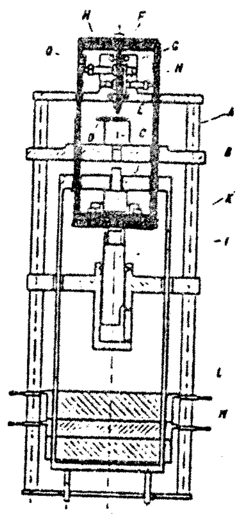
The complete test process on the Rockwell standardizing machine is the following. The weights necessary for the selected Rockwell method are placed or connected to frame K (Fig. 6). Sinking velocity of the hydraulic ram is adjusted in a dummy run, by observing the velocity of displacement of scale G in the microscope. Hereafter the ram is brought into its highest position. The block to be calibrated is fixed on worktable D. In the actual test cycle ram I is made to descend at controlled speed. Indenter E penetrates the block while the preliminary load frame H is transferred from ram I on the indenter. The vertical position of the indenter relative to the block is read on the measuring

(a)

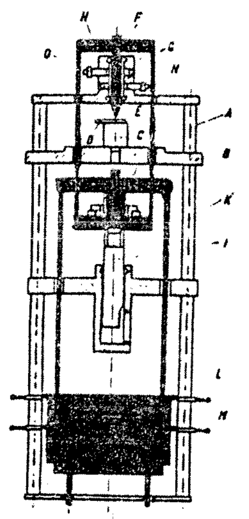




(b) Elements forming the machine frame



(c) Elements producing the preliminary test force



(d) Elements producing the total test force

Fig. 6. Rockwell standardizing machine (Kraftmessgeräte, Halle)

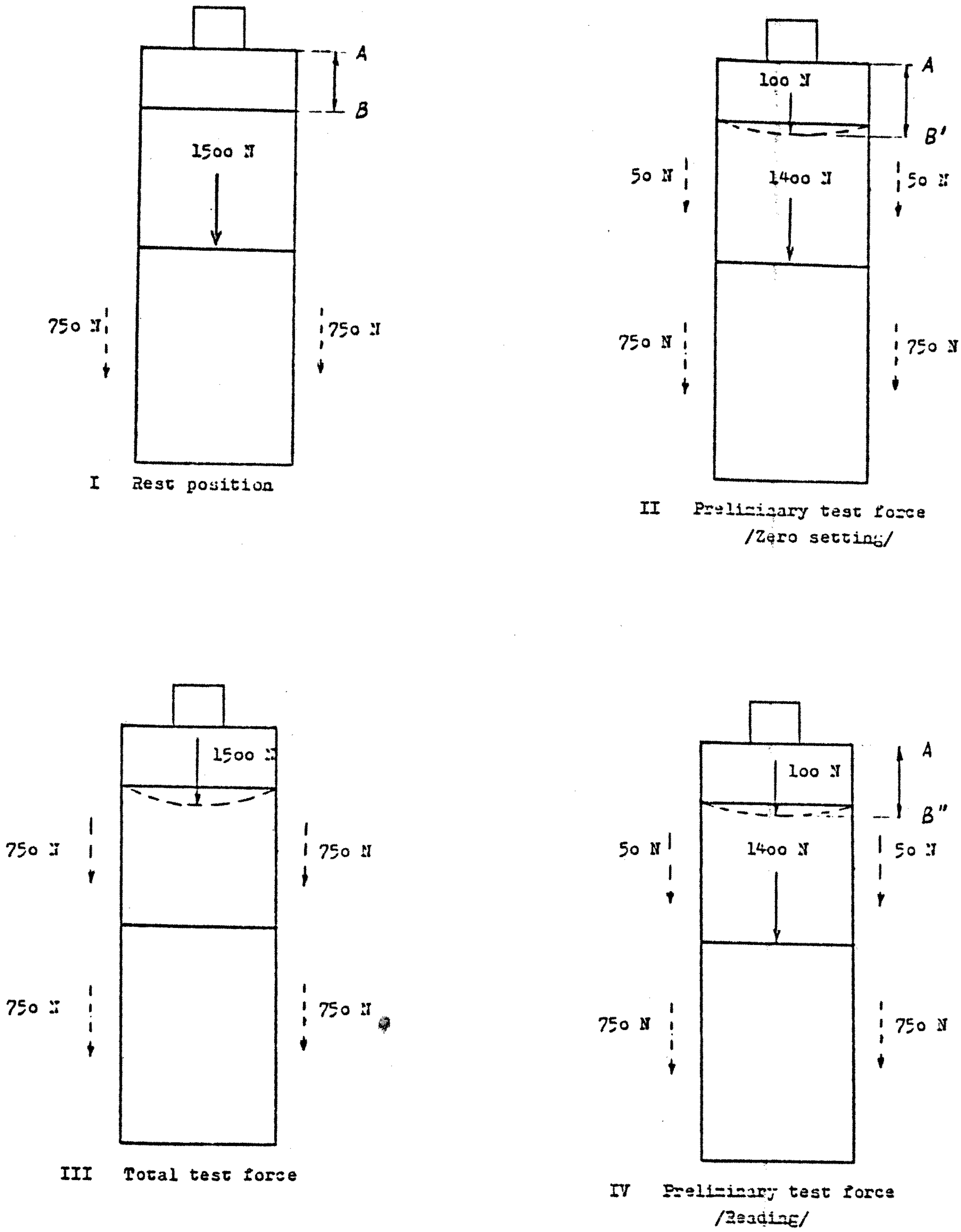


Fig. 7. Forces acting on the frame of the standardizing machine at the different stages of the Rockwell test cycle

device. Hereafter ram I continues its descent whereby additional load frame K is transferred to frame H, i.e. on the indenter. After a suitable interval the pump makes ram I to move upwards and the additional load frame will be supported again by the ram. The second reading of the measuring device is made. The difference between the two readings is the measure of Rockwell hardness. Then the upwards movement of the ram continues until frame H too will be supported by the ram. Thereby the indenter is raised from the block, the test cycle is completed.

Fig. 7 shows forces acting on the machine frame at the four stages of the Rockwell test (I to IV). For the sake of simplicity the figure was drawn under the assumption that 1 kgf $\cong$ 10 N. Arrows drawn in broken lines show loads in the different sections of the frame. The measuring microscope is arranged at the level A, which is not influenced by the application of test forces. The block is supported on level B which may be displaced by a force of 1 500 N at the maximum. The frame must be so rigid that deflection be negligible. When microscope readings are taken, only the preliminary force ($\approx$ 100 N) is acting so deflection is small. On account of hysteresis, however, the position of level B may, in principle, be different prior and after the application of the additional force (II and IV).

In the publication Hardness Standard Machines of National Institutes of Metrology [P-17] (editors PETIK and WEILER) the characteristics of the standardizing machines listed in Table 1 are described. Data on hardness scales realized by the respective machines, specifications of the measuring device, the method of load control, overall precision data of the equipment, and a photo or drawing of the machine are also included in this publication.

1.3. Specified requirements for hardness standardizing machines

Requirements for hardness standardizing machines can be found in standards and other prescriptions for hardness test blocks [SR-15, -16, -17, -18, -25, -26, -27, -28, -52, -53] (National standards which are harmonized with international documents are not included in this analysis).

The tolerance for the test force specified in international standard specifications is in general ± 0.1 %. But in some new ISO Standards this value was increased : For Vickers blocks 0.2 % [SR-17]. Preliminary load for Rockwell blocks 0.2 % [SR-15]. In the new edition of [SR-17], for the calibration of blocks for Rockwell superficial tests the preliminary load should be accurate to ± 0.5 %, the total load to ± 0.25 %.

The Japanese Standards [SR-52, -53] concern especially lever-type standardizing machines. The error of the mean value of three force measurements should not exceed ± 0.3 % of the Rockwell total test force, ± 1 % of the preliminary test force, and ± 0.2 % of the Vickers test force. The dispersion of the three measurements (max-min) may be equal to the one-sided error value, e.g. 0.2 % in the case of Vickers machines.

Table 1

Hardness standardizing machines included in [P-17]

Country	Institution	Machine	Hardness testing method: Rockwell	Rockwell Superficial	Vickers	Brinell
Australia	National Measurement Laboratory, West Lindfield, NSW	I	x			
		II			x	
Austria	Bundesamt für Eich- und Vermessungswesen, Wien	I	x	x	x	x
		II			x	
		III				x
Bulgaria	State Committee for Standardization, DKS Sofia		x		x	
PR of China	National Institute of Metrology, Beijing	I	x			
		II		x		
		III	x	x		
		IV			x	
		V			x	
		VI				x
		VII			x	x
Czechoslovakia	Československy metrologicky ústav, Praha	I	x			
		II		x		
		III			x	
		IV				x
F.R. Germany	Staatliches Materialprüfungsamt Nordrhein-Westfalen, MPA, Dortmund	I	x			
		II	x			
		III	x (with temperature chamber)	x		
		IV		x		
		V			x	
		VI			x	x
		VII			x	
		VIII				x
		IX				x
German Dem. Rep.	Amt für Standardisierung, Messwesen und Warenprüfung, Berlin	I	x			
		II		x		
		III			x	
		IV			x	x
		V				x

Country	Institution	Machine	Hardness testing method			
			Rockwell	Rockwell Superficial	Vickers	Brinell
Hungary	Országos Mérésügyi Hivatal, Budapest	I	x			
		II			x	
		III			x	x
		IV				x
Italy	Istituto di Metrologia "G. Colonnetti", IMGC, Torino		x		x	x
Japan	National Research Laboratory of Metrology, NRLM, Tsukuba	I	x	x		
		II			x	
		III			x	
Poland	Polish Committee for Standardization, Measures and Quality Control, PKNMiJ, Warsaw	I	x		x	
		II		x	x	
		III			x	
Soviet Union	Gosstandard, VNIIFTRI, Moscow	I	x	x		
		II			x	
		III			x	
		IV				x
		V				x
United Kingdom	National Physical Laboratory, NPL, Teddington	I	x			
		II		x		
		III			x	
		IV			x	
	Aeronautical Quality Assurance Directorate, Harefield, Uxbridge	V				x

The mechanism controlling the application of force must have either

- a device for reducing the speed of penetration, or
- a regulating device for keeping the speed of penetration constant.

In machines of the first type the initial speed of the indenter, before it penetrates the block, must not exceed 1 mm/s.

In machines of the second type, the speed of penetration must be between 3 and 12 μm/s. In the new series of ISO Standards this specification was maintained only for the calibration of Rockwell blocks, with a range of 5 to 20 μm/s.

Other specifications for the loading cycle are summarized in [P-21].

A single prescription for verification of hardness standardizing machines is known, published in the German Democratic Republic [SR-51], denoted ASMW-VM 145. This prescription applies for the specific machine design shown in Fig. 6. In the following some of the specifications contained in [SR-51] will be quoted.

A standardizing machine can be used only for a limited range of test forces. The ratio of the lowest and highest test force (F_{max}) that can be applied on a standardizing machine is specified in [SR-51] as follows :

1:10 if $F_{max} \leq$ 100 N
1:15 if $F_{max} =$ 450 - 1 500 N
1:25 if $F_{max} \geq$ 1 500 N

The worktable on which the block being calibrated is arranged (C in Fig. 6) should be made of heat treated high strength steel, have a fine ground surface, shall be plane or moderately convex (maximum deviation from the plane 3 μm on a length of 60 mm). Planeness should be checked by a plane parallel glass. The specified convexity corresponds to max. 12 interference rings which should move outwards if the glass is pressed to the surface.

The switching and control elements, pump, motor, and other sources of possible vibration should be mounted in a separate unit, connected only by elastic elements (wires, tubes) to the main structure of the machine, which is shown in Fig. 6.

The machine should be stable, the supports adjustable to ensure a horizontal position of the worktable within ± 1'. The worktable shall not be vertically displaceable.

The lateral movement of the loading frame should be prevented by restraints arranged lower than the centre of gravity of the weights. Wires necessary for signal lamps and other purposes should not impede the free vertical movement of the loading frames.

Maximum permissible error of the weights and loading frames, taking into consideration also local gravity and air buoyancy, is ± 1 x 10^{-4}. The permissible relative error of the preliminary force for Rockwell tests is ± 2.5 x 10^{-3}, that of other test forces ± 1.5 x 10^{-3}.

[SR-51] considers the verification of a hardness standardizing machine as a procedure of tracing the hardness value to another hardness standard which is at a higher level in the hierarchal order. Traceability is checked by measurement of selected high quality hardness test blocks. (Range of values not more than 40 % of the value specified for current usage). Maximum permitted deviations are specified for the various scales as follows :

HRC	± 0.30 HRC
HRN 30	± 0.50 HRN 30
HV	± 0.5 % of the hardness value
HB	± 0.5 % of the hardness value.

The deflection of the frame of Rockwell standardizing machines (discussed earlier in connection with Fig. 7) shall be checked by the following method : In the place of the indenter a component of similar stem and of a flat or slightly convex lower face (Fig. 8) is clamped. This dummy indenter is contacted with the worktable under preliminary force. The position of the measuring device is read. The force is increased to total force and the depth measuring device read again. The same is done after having reduced the load to the preliminary force. This procedure is repeated 20 times. The deflection of the frame at the effect of increasing the preliminary force to total force is denoted by f_1. The negative deflection at the effect of changing from total force to preliminary force is f_2. The difference of the means of the values obtained in 20 measurements is the relaxation Δf of the machine frame :

$$\Delta f = \overline{f_1} - \overline{f_2}$$

KERSTEN [K-2] published the results of deflection measurements on machines of various frame designs. At the effect of an additional load of ≈ 1 400 N (140 kgf), Δf values were found to be in the range of 0.01° to 0.24 μm, what represents an error of about 0.1 HRC at the maximum.

Other prescriptions contained in [SP-51] will be mentioned in connection with the discussion of individual parts of the standardizing machine.

The permitted relaxation of the frame of lever-type machines is specified in [SR-53]. Δf values should be determined for each test load separately, and should not exceed 0.2 HR for Rockwell, and 0.3 HR for Rockwell Superficial hardness. This value used to be employed as a correction to measured hardness values.

1.4. Configuration of realized standardizing machines

In this chapter the characteristic features of various hardness standardizing machines will be discussed. Older types are also included, and not only for the sake of historical interest. Experience shows that designers often return to earlier solutions which were abandoned for some reasons.

1.4.1. Deadweight standardizing machines for the Rockwell test

The first machines were developed for the unification of the Rockwell C scale. Even today this hardness testing method has the greatest number of standardizing machines, in conformity with its share in hardness testing practice. Many Rockwell standardizing machines, however, can be used for other methods too. And many design principles employed on Rockwell machines are equally applicable on machines for other methods.

The arrangement shown in Fig. 6 is the late version of a long process of development, which has its origins in the first standardizing machine set up by MEYER in 1943 [M-24, M-11, M-12] (called also the MEYER-WAZAU type). The first pattern of the machine, with the weight for preliminary force still above, is shown in Fig. 9. The left side of the figure shows the principle, the right side is the actual realization of the design [W-6].

A later version of the machine is shown in Fig. 10 [H-9]. The measuring microscope was first arranged in position B. Later, to improve accuracy, it was transferred to position A, nearer to the indenter. This machine was later equipped with a heating and cooling device [L-6] permitting the calibration of blocks at temperatures up to 500 °C and down to - 156 °C.

A machine with all loading weights above the indenter is mentioned in [W-13, Fig. 155].

The first version of the Rockwell standardizing machine of the National Physical Laboratory, Teddington, built around 1945, is shown in Fig. 11 [P-13, M-3, M-6]. The framework of the machine is formed by four columns. The frictionless support of the indenter, together with the preliminary load asembly b deserves special mention. The assembly has freedom of movement only in a vertical direction ensured by means of four pairs of tensioned steel wires (Ø 0.8 mm) passing between opposite corners of the machine, as shown at the right side of Fig. 11. Two pairs of wires are fitted to the top, and two to the bottom of the preliminary load frame. These wires, which serve merely as guides, are adjusted to very small tensions.

Indentation depth was measured on this machine by an optical comparator of the tilting-mirror type with a magnification of about 1 600, readings being taken from a projected scale.

The schematic diagram of the Rockwell standardizing machine built at the NPL around 1960 is shown in Fig. 12 [M-4, M-6, N-2]. The stationary parts of the machine framework are drawn in grey, the loading elements in black, while the moving actuating elements in white. In rest position the preliminary load pan B is supported by three rods H, 120 degrees apart in asimuth, whose top surfaces are co-planar. Similarly the additional load pan G is supported by the three rods J. The six supporting rods H and J are rigidly attached to a table K which is driven up and down by an hydraulically operated ram N. Connection between the two load pans is ensured by a double knife-edge arrangement F (for more details see [M-4]). Before operation, the centres of gravity of the load pans and the position of the line of action of the double knife-edge are adjusted in dummy runs, so that they

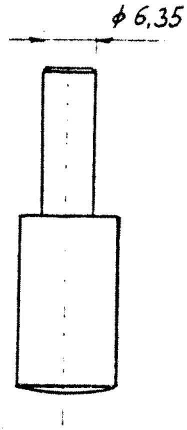


Fig. 8. Dummy intender for checking machine deformations

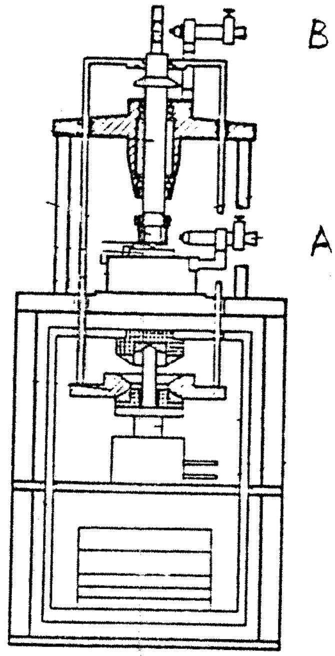
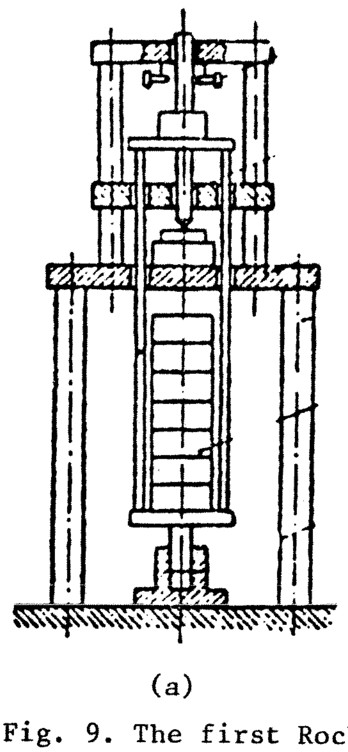
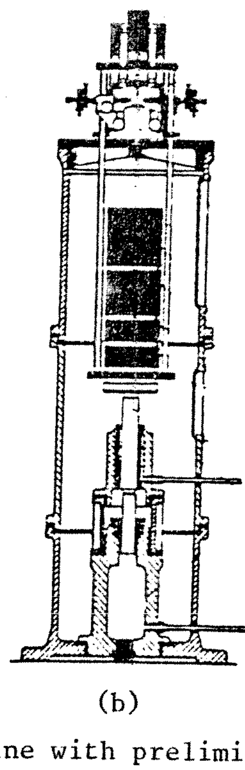


Fig. 10. Rockwell hardness standardizing machine. Two arrangements of the measuring microscope



(a)



(b)

Fig. 9. The first Rockwell standardizing machine with preliminary load weight above the indenter. (Meyer-Wazau)

(a) Principle (b) Actual design

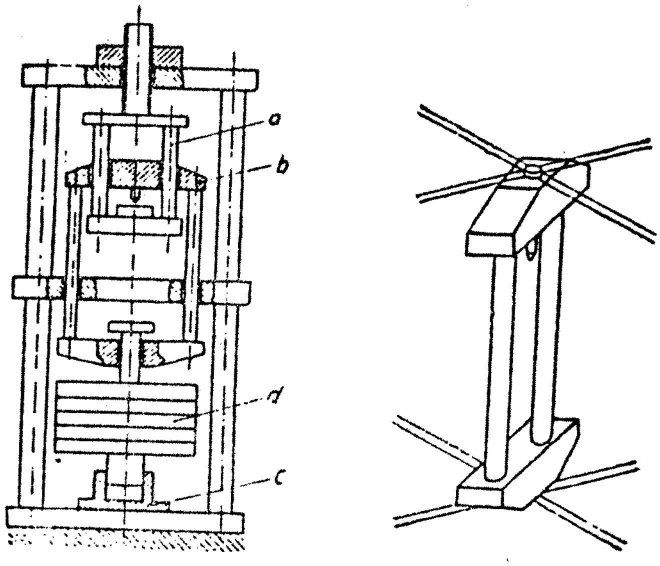


Fig. 11. Rockwell hardness standardizing machine.
(NPL, Teddington)

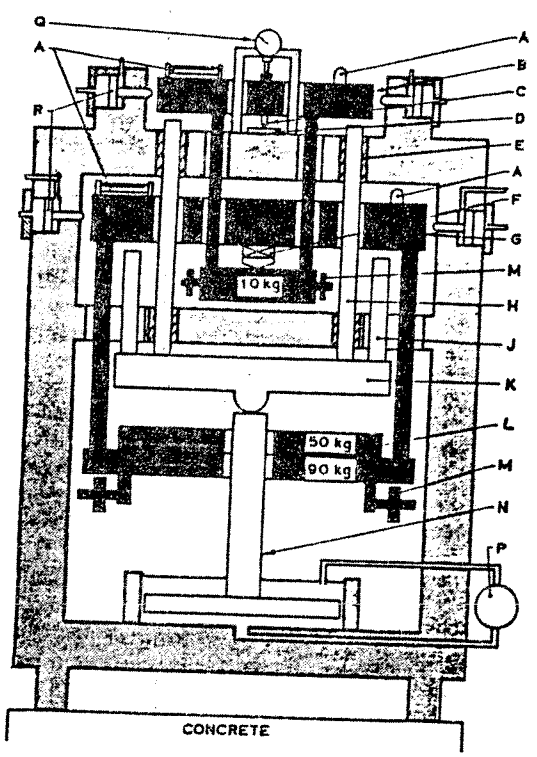
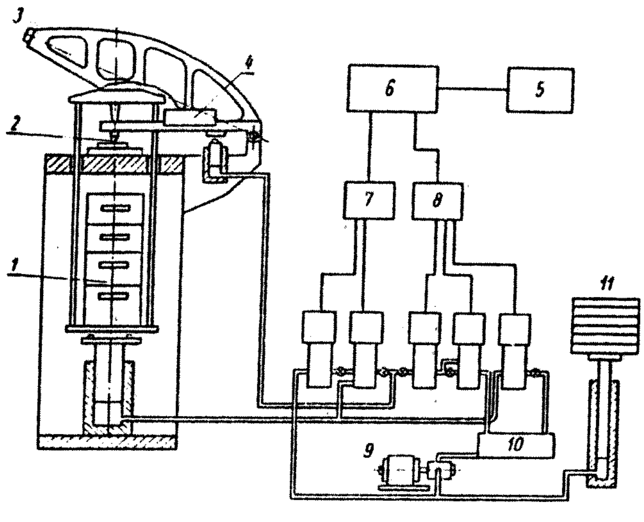
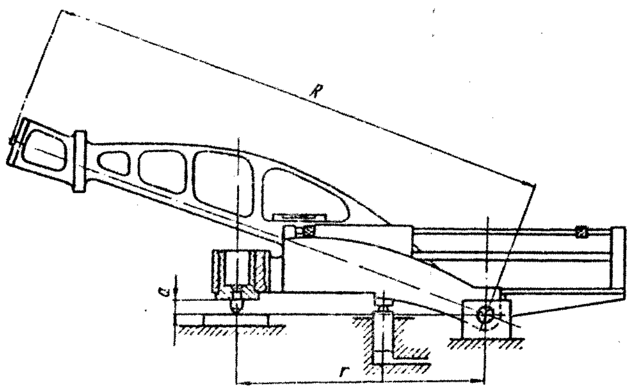


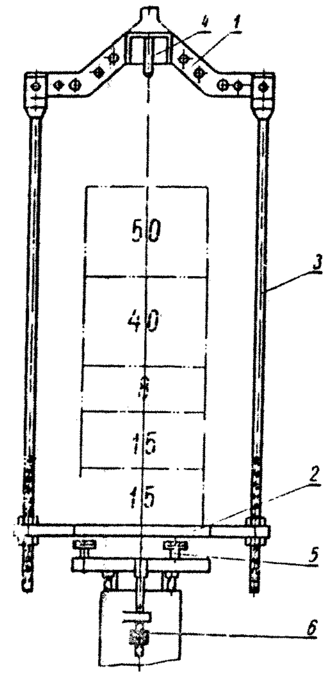
Fig. 12. Schematic diagram of Rockwell standardizing machine (NPL, Teddington)



(a)



(b)



(c)

Fig. 13. Rockwell hardness standardizing machine (Mendeleev Institute, Leningrad)

(a) General scheme
(b) Preliminary load lever
(c) Additional load dead weights

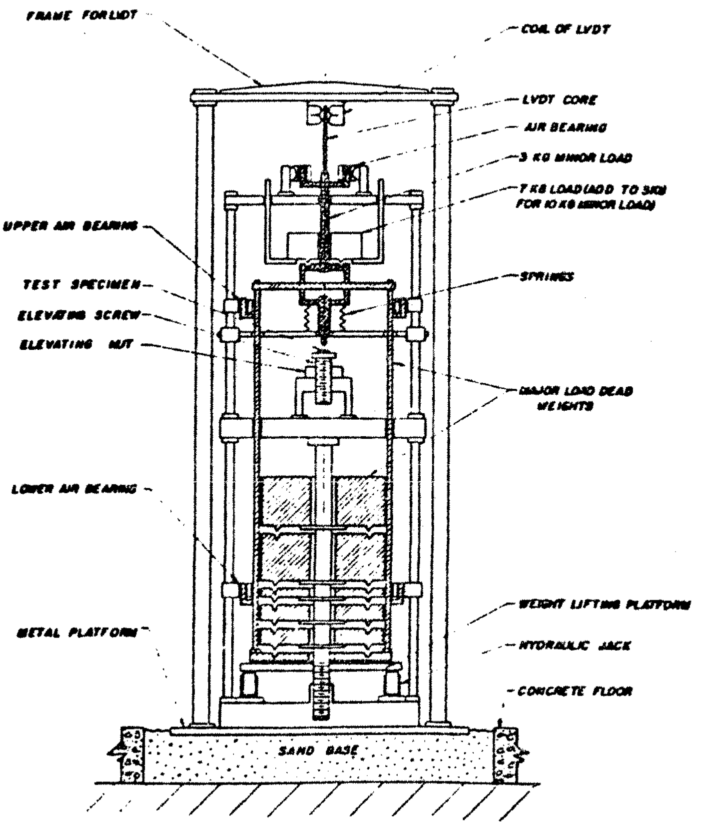


Fig. 14. Schematic of ACCO-Wilson dead weight standard hardness testing machine

are exactly below the point of the indenter. This condition is achieved and maintained by adjustable balance weights M and level tubes A attached to the load pans and by hydro-pneumatically operated pushers and stops R which, after each cycle of indenting, automatically return the two pans to predetermined positions. The relatively complicated adjustment procedure is necessary, because the indenter or the load pans have no lateral guidings. During the indentation process weights are hanging freely on the indenter without any element that may cause friction.

The first Rockwell standardizing machine of the Mendeleev Institute, Leningrad can be seen in Fig. 13 [S-4, S-7]. (In [S-4] the inscriptions of the figures showing Rockwell and Vickers machines are confounded). The schematic diagram (a) shows two noteworthy features. Hydraulic accumulator 11, arranged in a separate control cabinet, can actuate the machine with switched off motor so as to prevent vibration effects. The other is the pivoted lever shown in Fig. 13 (b), which carries the indenter, represents the preliminary force and carries the depth measuring scale 3 at its extremity. The lever is actuated by a hydraulic ram. Since the indenter is moving on an arc of r = 300 mm, the surface of the block is to be arranged precisely in the same level as the pivot. Dimension a is also important in this respect. The vertical position of the indenter is checked by a bubble level, so that its deviation should not be more than 3'. Under these conditions the displacement of the indenter point during the test process in the horizontal direction is less than 0.07 µm. Pivot friction represents less than 0,15 % of preliminary force. Additional load is hanged on by means of frame (c), its relative accuracy was 5.10^{-5}. Indentation depth is measured by a microscope with ocular micrometer fixed to the stationary part of the machine frame.

The dead-weight Rockwell hardness standard of ACCO-Wilson (USA) is shown schematically in Fig. 14 [D-2]. Important features in this design are the air bearings for frictionless application of all forces for Rockwell and Rockwell superficial tests, and a linear voltage differential transformer to measure the depth of the indentation. If at any time during the test there happens to be a contact between the preliminary or additional load frames and the shell of the air bearing, this fact will be registered by corresponding meters. In the event that contact was indicated, the test is rejected, but this is a rare occurence.

To simulate application of the preliminary force on commercial hardness testers, the tested block is arranged on a table raised by an elevating screw, whereby the force is increased to 98.1 N. The springs shown in Fig. 14 help to produce a force application similar to that on commercial testers. All test functions are performed automatically, under the control of the operator.

From the newest standardizing machines, that of the Colonnetti Metrological Institute, Torino is worth mentioning [B-1]. Fig. 15 (a) shows the scheme of the machine at rest, before starting the test cycle. Fig. (b) is the moment when additional force is added to the preliminary force.

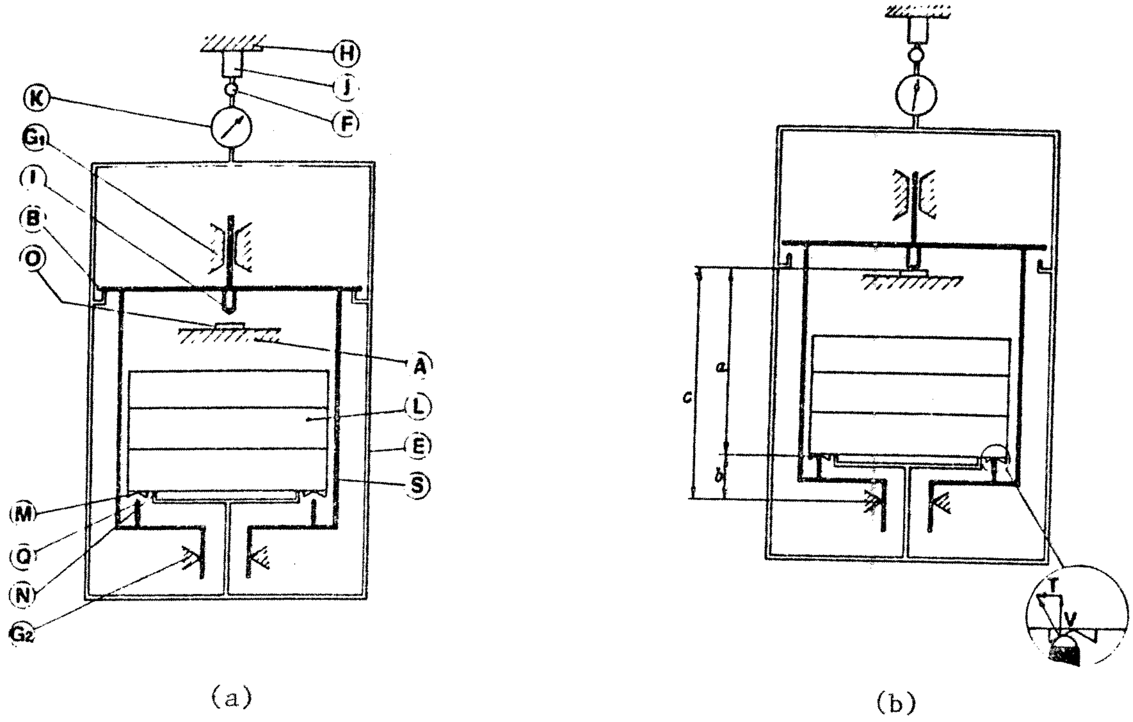


Fig. 15. Scheme of the main components of the IMGC, Torino hardness standardizing machine

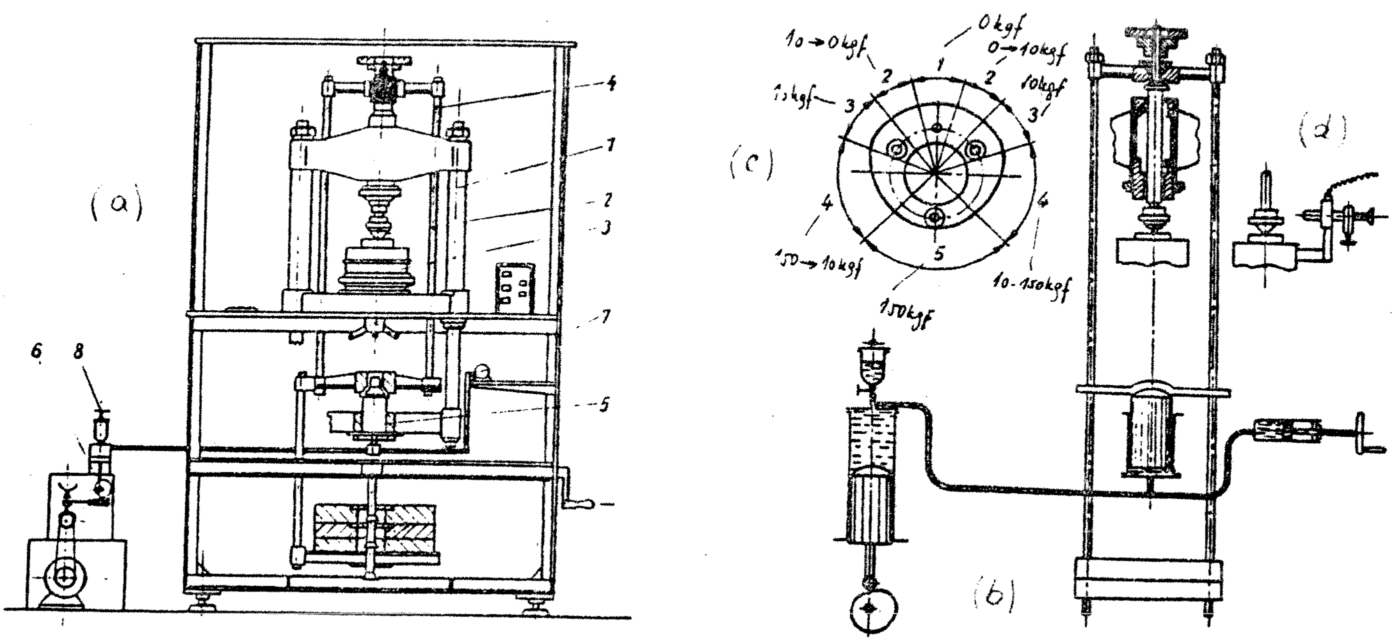


Fig. 16. Rockwell standardizing machine
(a) General scheme. (b) Scheme of the controlled cycle loading mechanism. (c) Control cam.
(d) Indentation depth measurement (Rumanian Metrology Institute)

The stationary frame of the machine includes worktable A supporting the block O, the outer shells of air bearings G1 and G2. At the top of the frame, on crosshead H hangs hydraulic jack J. This jack moves the lifting frame E, through elastic hinge F and load cell K. Carrying pads B and N are mounted on the lifting frame serving to support preliminary load frame S and the weight stack L, respectively. The pads do not provide side constraints. Preliminary load frame S carries the indenter I, the supporting plates mating with pads B, and spherical ended rods Q mating with vee-notches M to ensure a kinematic support and repeatable positioning of weight stack L.

When test forces are applied, swing of the frames is prevented by air bearings G1 and G2 without influencing test forces exerted by dead weights. At the lower right side of Fig. 15 (b) vee-notch M and spherical ended rod Q are shown in a critical operating phase, at the transitory position when the weights are supported by both frames E and S. At this moment a transient lateral component of force T arises which is taken up by the lower air bearing and, to a much lower extent, reduced in the ratio b/c, by the indenter. Proper alignment of the machine components limits this lateral force to less than 0.01 % of the main load. In actual operation G2 is hardly called upon to act at all.

By applying proper distance pieces on pads B, weight stack L is placed on frame S before the indenter contacts the block. This is the process necessary at Brinell and Vickers tests.

Indentation depth is measured by a laser interferometer which will be discussed later. The designers [B-2] are of the opinion that the use of air bearings considerably reduced production costs. Otherwise prevention of swing and inclination of the indenter axis with respect to the normal of the block surface would have required a much higher precision of machining.

The Rockwell standardizing machine developed in the Rumanian Metrology Institute at Timisoara is shown in Fig. 16 [R-1, -4, -6]. At the time of constructing this machine the controlled loading cycle was a novelty. In part (b) of the figure the cam, which makes one turn in a minute, is shown to actuate a piston, transmitting oil pressure to the ram actuating the loading frame, which has similar design solutions as the machine shown in Fig. 6.

A similar machine of Japanese design [Y-9] is shown in Fig. 17.

The Rockwell and Rockwell-Superficial hardness standardizing machine of the National Institute of Metrology, Beijing, China [T-4] can be seen in Fig. 18. Depth measurement by a laser interferometer will be discussed later. Given accuracy for the preliminary force is $\pm 1 \times 10^{-4}$.

The various elements, including hydraulic and electronic control, evaluation and display of results, necessary on a hardness standardizing machine, are shown in Fig. 19 and 20 (Czechoslovak Metrology Institute) [C-7].

For research purposes a Rockwell-Vickers-Brinell hardness standardizing machine has been developed by WEILER and SCHIMMER [W-8] in which three kinds of indenter penetration can be realised : the

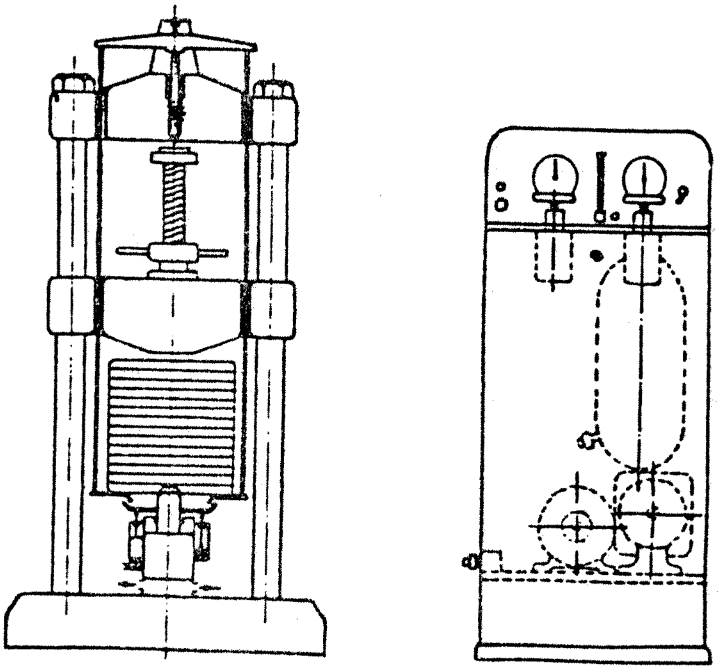


Fig. 17. Japanese dead-weight hardness standardizing machine

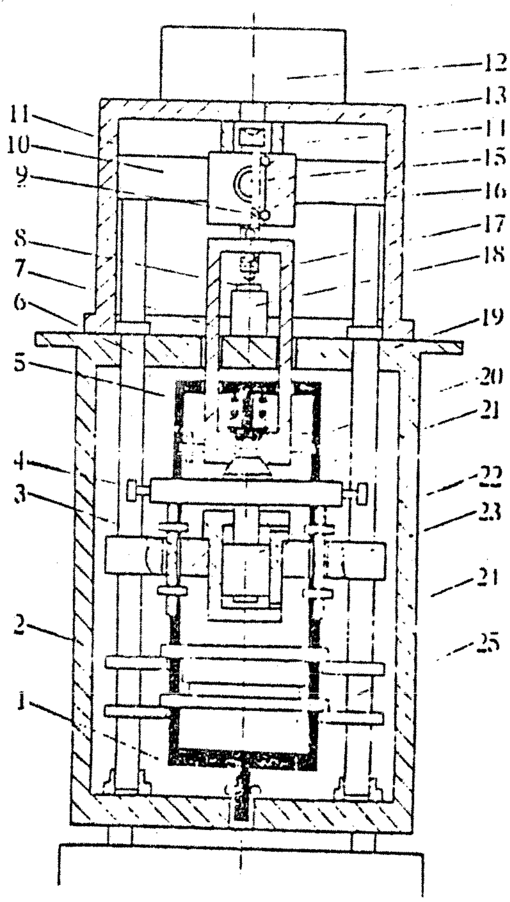


Fig. 18. Rockwell and Rockwell Superficial hardness standardizing machine (National Metrology Institute of China)

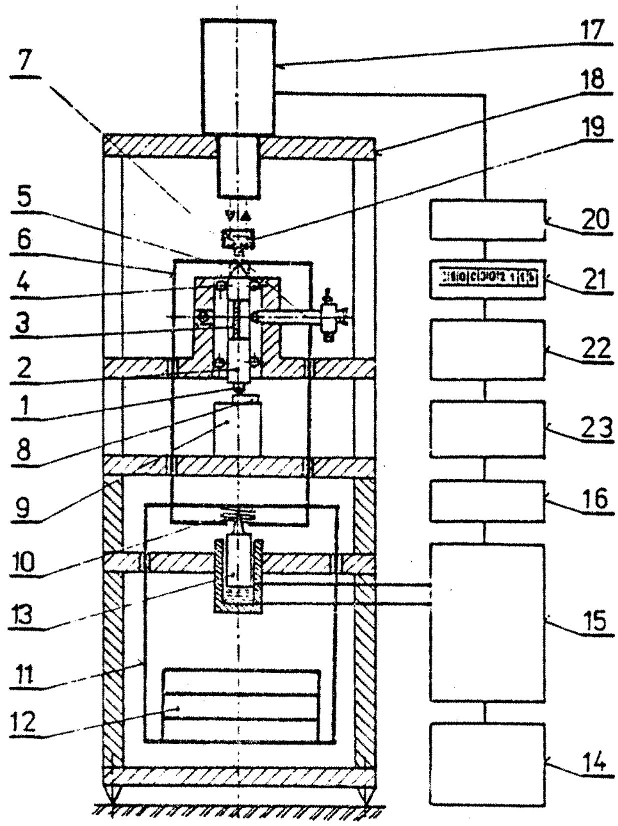


Fig. 19. Scheme of the elements, control and indicating organs of the Czechoslovak Rockwell standardizing machine
1 - indenter, 2 - plunger, 3 - divided scale, 4 - guiding of the plunger (ball bearing), 5 - spring, 6 - upper loading frame, 7 - measuring microscope, 8 - block being calibrated, 9 - work table, 10 - main spring, 11 - lower loading frame, 12 - weights, 13 - piston, 14 - hydraulic source, 15 - hydraulic circuit, 16 - electronic control, 17 - laser-interferometer, 18 - laser support, 19 - prism, 20 - laser source, 21 - evaluation of the laser, 22 - counter, 23 - printer

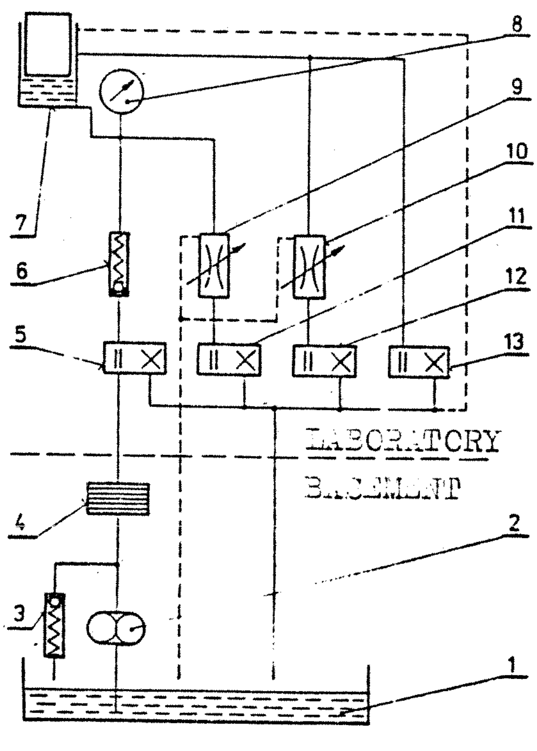


Fig. 20. Hydraulic circuit of the machine shown on Fig. 19
1 - oil sump, 2 - pump, 3,6 - non-return valve, 4 - oil filter, 5,11,12,13 - solenoid valve, 7 - cylinder, 8 - manometer, 9,10 - control valve

conventional, i.e. penetration without control ; penetration with constant speed of force increase ; penetration with constant speed.

1.4.2. Deadweight standardizing machines for the Vickers test (from HV 10 to HV 100)

These machines are similar to those serving for Rockwell measurements, but the design is more simple : No preliminary load frame is necessary and the loading cycle consists of less steps. Indentation measurement, in general, is performed on separate measuring microscopes, which are not incorporated in the standardizing machine ([C-6], [H-8], [M-12], [S-4], [S-12]).

The design of the NPL Vickers machine (Fig. 21) [M-2, M-3] is based on the Rockwell machine shown in Fig 12, some details, however, deserve mentioning. The scale pan represents the lowest test force of 294.2 N (30 kgf)., which can be increased by additional weights to 490.3 N (50 kgf), 980.7 N (100 kgf) and 1176.8 N (120 kgf), respectively. The forces are correct to ± 10 N. The top surface of the scale pan carries two level tubes mounted mutually at right angles and having a sensitivity such that one division of 2.5 mm spacing is equivalent to 3 seconds of arc tilt. A pneumatic gauging head indicates when the scale pan leaves the table supporting it. The hydraulic ram consists of a 150 mm diameter shaft running in Oilite bearings, and this shaft is integral with a 254 mm diameter piston which moves in a ground cylinder having a diametral clearance of 25 µm with respect to the piston. The space above the piston constitutes the reservoir for an oil of suitable viscosity, and movement of the table and scale pan is effected by slowly pumping the oil from above to below the piston, and vice versa.

Due to the large diameter of the piston and the small delivery of the pump, velocities of a few micrometers per second can be achieved readily, and movement of the ram is completely free from stick slip phenomena, because of the small but significant clearance between piston and cylinder. Leak past the piston is constant regardless of the load on the scale pan, and constant velocities of the ram between zero and about 1 mm/s are obtained either by setting the swash plate of the pump or by changing its speed of rotation. The latter can be increased, by a factor of nine, when rapid traversing of the table is required.

An accessory is a pantograph mechanism which moves the test block between indentations by means of an arm remote from the machine. This pantograph facilitates the precise location of indentations at predetermined positions on the test block, and has assisted in establishing correlation between hardness and differences of microstructures in localised areas.

1.4.3. Standardizing machines for low load Vickers scales

Below HV 10 most institutes of metrology use commercial low load Vickers hardness testers for block standardizing purposes, after having checked the metrological characteristics of the apparatus, especially those of the indenter.

A machine developed specially for standardizing purposes was described by HORMUTH [H-8].

1.4.4. Deadweight standardizing machines for the Brinell test

In this chapter Brinell standardizing machines suited to produce the test force of 29.42 kN (3000 kgf) are described [C-5, R-2, L-3].

The working principle of these machines is similar to that of the Vickers machines, but on account of the considerably higher test forces the structure is more robust and larger. At the displacement of 3 tons of deadweights high inertia forces may arise with undesired effects on the measuring process. To prevent this, the strong conical spring 12 in Fig. 22 damps oscillations [C-5]. load frame 5 connected by means of spring 4 to the spindle carrying the indenter produces the lowest test force, 1226 N (125 kgf). Other forces are produced by dead weights 8 arranged on frame 7

The machine shown in Fig. 23 [R-2] is equipped with the loading cycle control equipment which was discussed in connection with Fig. 16. Hand operated hydraulic cylinder 14 serves to adjust the position of the indenter according to the thickness of the measured block.

A new Brinell standardizing machine (State standard of the Soviet Union) was set up in 1985 with the special aim of extending the measuring range up to 650 HBW, a hardness value determined by means of hard metal ball (Fig. 24). The hydraulic system is characterized by a dead-weight loaded pressure limiting piston-cylinder assembly A, and by two cylinders 2 actuating the 3 tons of dead-weights for the test force [B-15].

1.4.5. Some important details of design

As we saw in the preceding chapters, guiding of the indenter is a decisive element of the design of hardness standardizing machines. The indenter should have a stable, exactly vertical position while the force acting on it is changed repeatedly. There should be no lateral forces and no friction impeding the action of the test force. The principles employed on the machines discussed in the precedings are summarized in Fig. 25. The first, shown in Fig. 25 (a) is the solution employed in the machines shown in Figures 6, 10, 16, 18, 22, 23 and 24. The plunger carrying the indenter is not connected rigidly with the loading frame. The indenter is moving in guides, the frame is free to make very little swings. In one design the guide consists of 6 ball bearings, arranged at two levels with their axes horizontal (Fig. 26). Three bearings at each level surround the stem of the indenter, arranged at angles of 120°. In Fig. 26 the old and the new solution of a guiding are shown. By increasing the distance between the two levels of the bearings, accuracy was increased. KERSTEN [K-2] examined the accuracy of guides of this type. The error appearing in depth measurement on account of bearing imperfections may amount to 0.1 µm ($\hat{=}$ 0.05 HRC). By using selected ball bearings and by correct adjustment this error can be reduced to a tenth. [SR-51] specifies the method for detecting friction caused by the guide: A dynamometer clamped in the standardizing machine is loaded with the preliminary test force of 98.07 N (10 kgf). The sensivity of the machine is checked by additive weights corresponding to 10^{-3} of the force (≈ 0.1 N). At the addition of 0.1 N the indication of the dynamometer should change by at least 0.09 N.

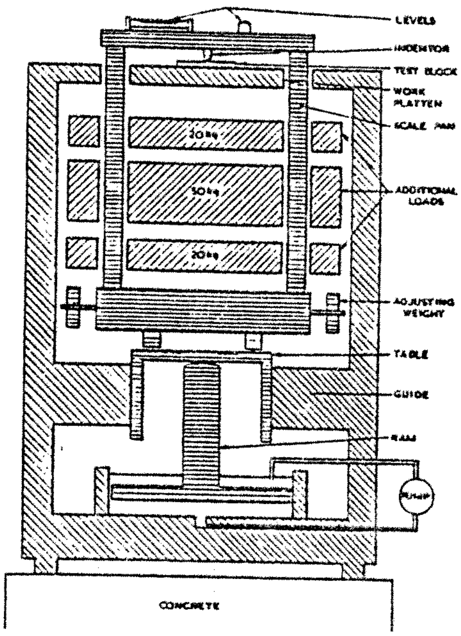


Fig. 21. Vickers hardness standardizing machine (NPL)

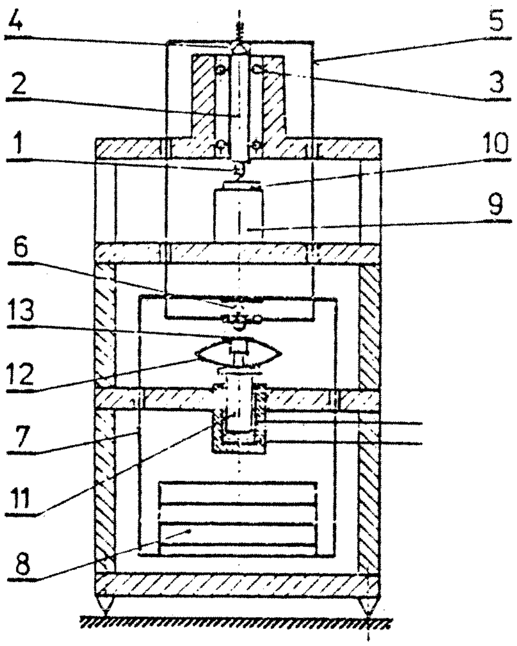


Fig. 22. Scheme of a Brinell standardizing machine (Czechoslovak Metrology Institute)

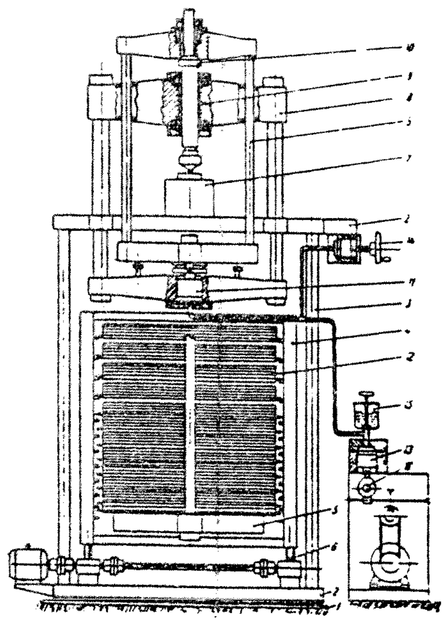


Fig. 23. Brinell hardness standardizing machine (Rumanian Metrology Institute)

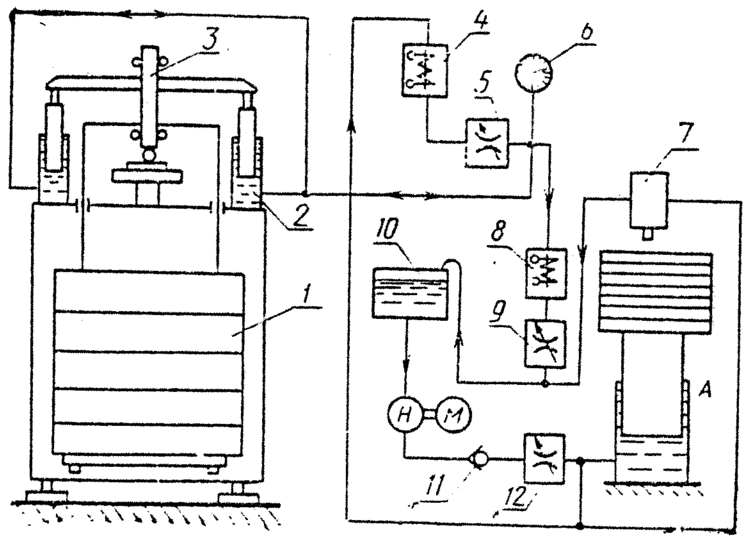


Fig. 24. Scheme of a Brinell standardizing machine (VNIIFTRI, Moscow)

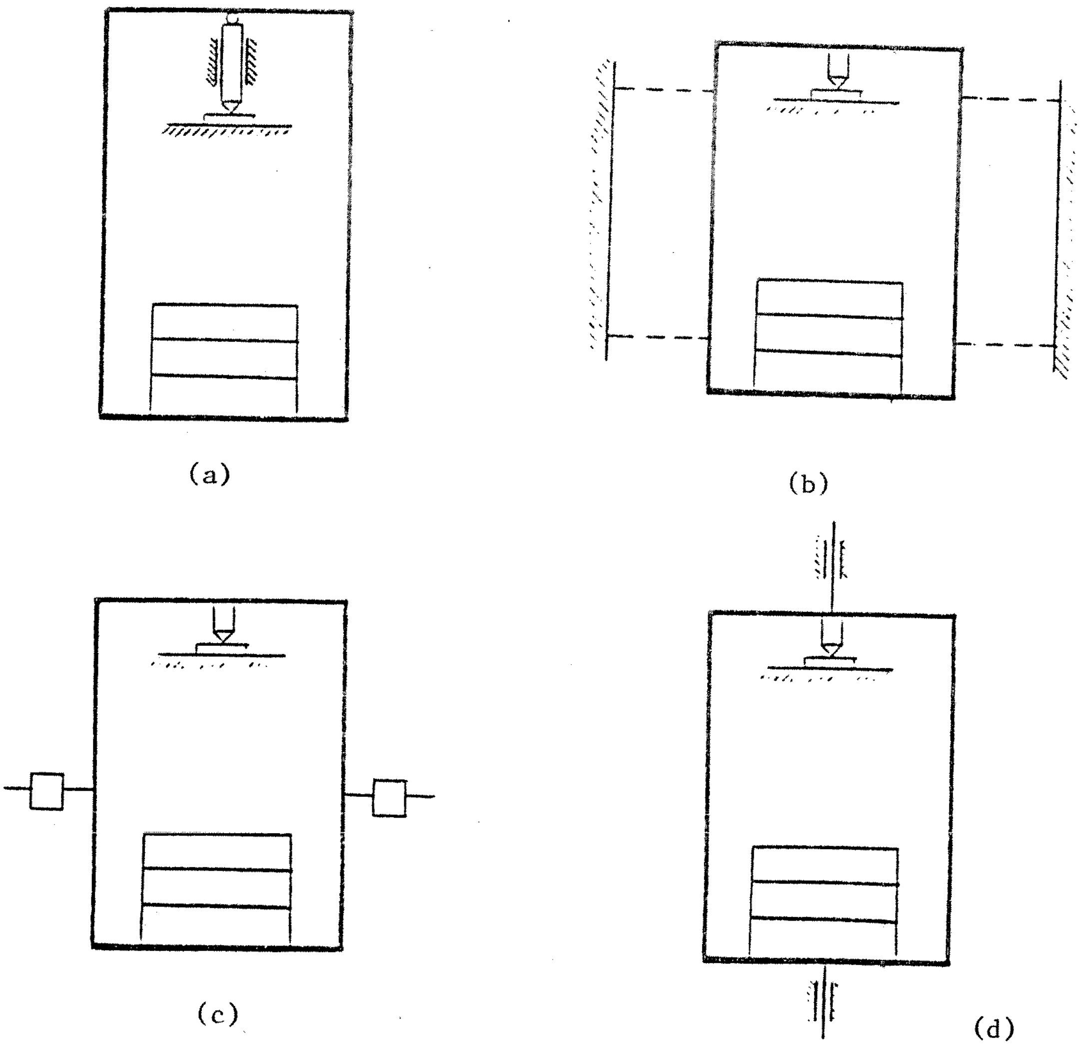


Fig. 25. Various ways of ensuring the vertical position of the indenter

The principle of indenter guiding shown in Fig. 25 (b) was employed on the machine shown in Fig. 11. The indenter is rigidly connected to the loading frame, similarly as in systems shown at (c) and (d). The frame of Fig. 11 (b) is guided by horizontally tensioned wires. The wires permit only a very small displacement of the indenter without influencing the test force.

The principle shown in Fig. 25 (c) was employed on the machines shown in Fig. 12 and 21. This design requires high dimensional accuracy for the elements of the loading frame and an adjustment operation in dummy runs before starting tests. Adjustments are made by the help of the level tubes arranged on the load pan and by adjustable balance weights.

In case of the principle shown in Fig. 25 (d) frictionless air-bearings guide the loading frame. This design principle was employed on the machines shown in Fig. 14 and 15.

Another important element in the desing of standardizing machines is the clamping of the indenter.

The indenter is often removed from the machine. Therefore it is important that its clamping should ensure correct positioning and freedom from "settling" (In any case three not evaluated indentations should be made after having clamped the indenter so as to ensure its stable position).

Some designs of indenter clamping devices are shown in Fig. 27 [P-17, B-12]. (a) shows clamping by a threaded cap and a self-aligning insert. Fitting is ensured by the stem of the indenter. (b) and (c) show similar arrangements for the case that the lower shaft of the indenter has a larger diameter. The same principle employed for a Brinell indenter is shown in Fig. 27 (d). Another variant of (a) is shown under (e) where a packing is inserted between the cap and the indenter. The indenter shown at (f) is fixed by a wedge tensioned by a screw. At (g) a rapid clamping device can be seen. Two springs draw the indenter upwards by means of a small joke with conical hole. Another rapid clamping device is shown at (h). A location pin fixed by a spring steel band enters the groove machined on the stem of the indenter. Two variants of clamping by the help of a draw bolt are shown at (i) and (j). The difference between these two solutions is the place of location. At (i) the shank, at (j) the largest diameter of the indenter body is ensuring location by a suitable clearance.

Finally a solution frequently employed on commercial hardness testers, which should, however, be avoided in standardizing machines, is shown in Fig. 28 for the sake of comparison. Tensioning by a lateral screw does not secure a fixed position of the indenter.

1.4.6. Lever type standardizing machines

The designers of the Rockwell standardizing machine of the National Research Laboratory og Metrology, Japan preferred a lever type arrangement. In their opinion the loss of accuracy of the test force in lever type machines is compensated by avoiding possible friction and swinging motion of the dead-weight assembly [Y-5, Y-6, Y-17, Y-24, Y-25]. The schematic diagram is shown in Fig. 29. Some interesting design

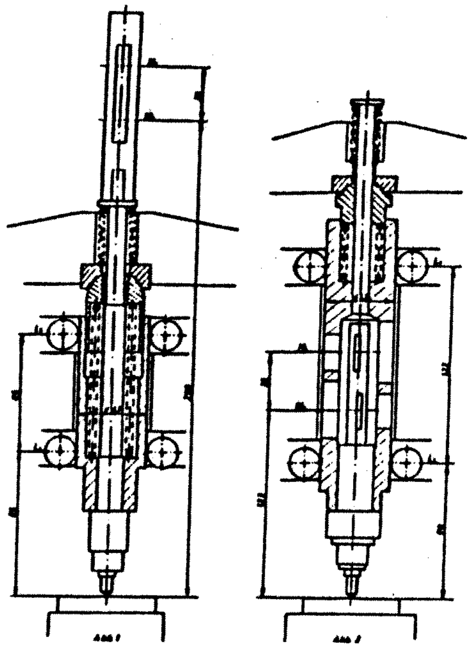


Fig. 26. Guiding the indenter

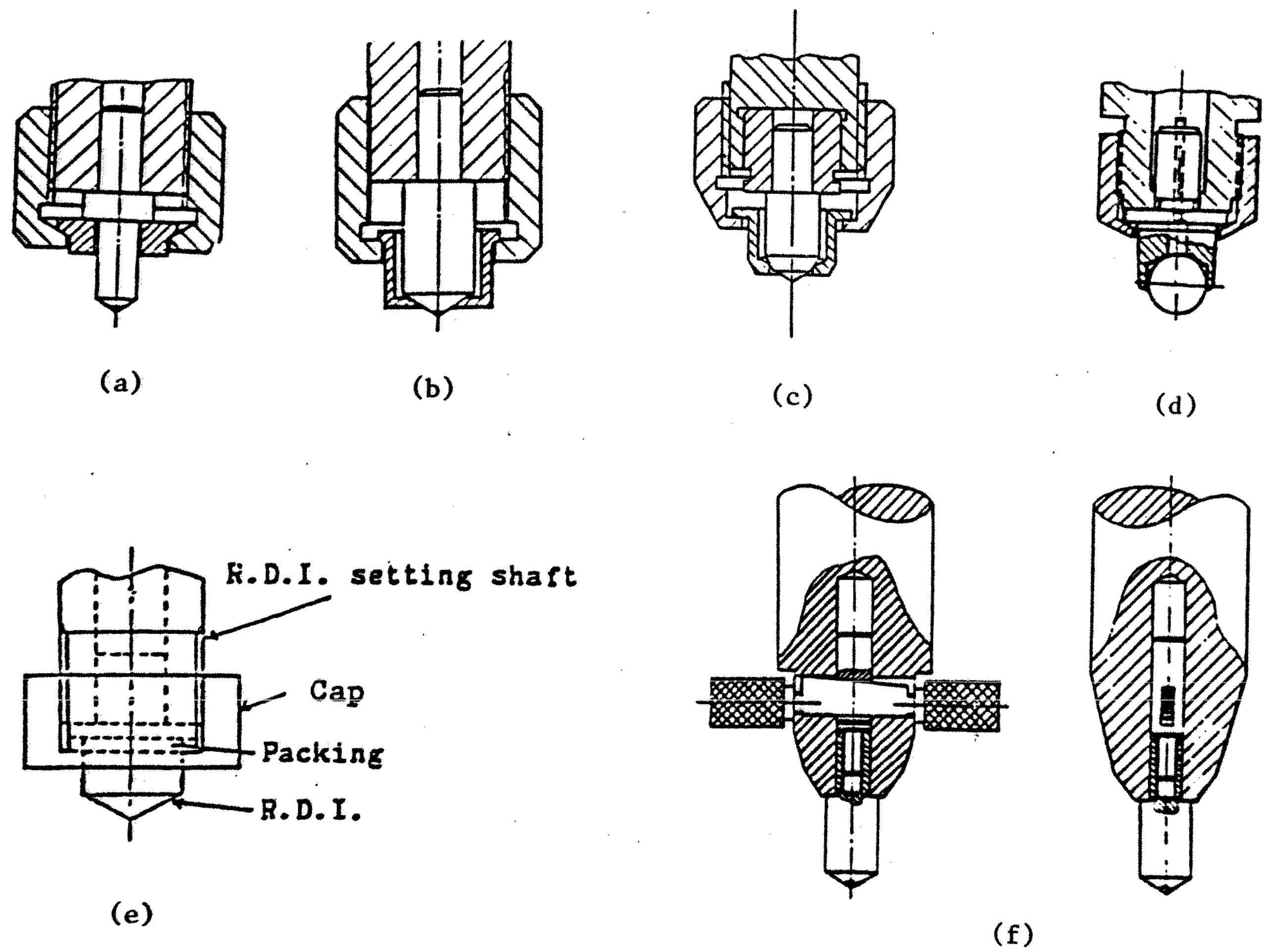
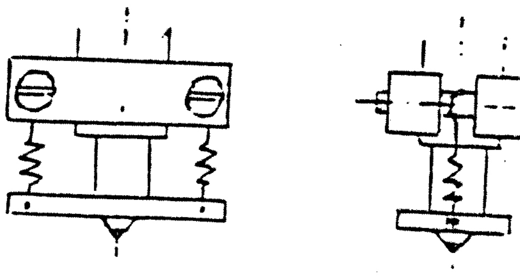
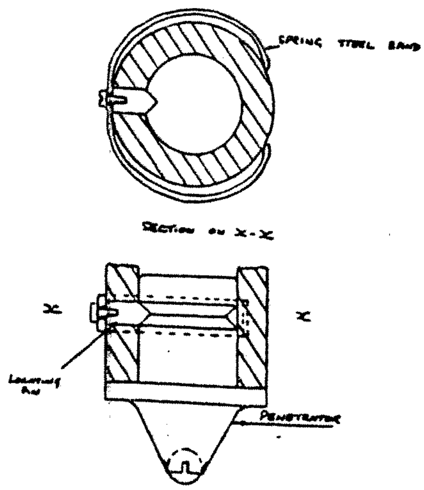


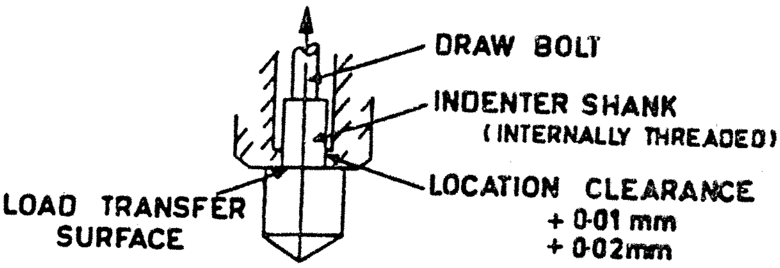
Fig. 27. Various methods of clamping indenters



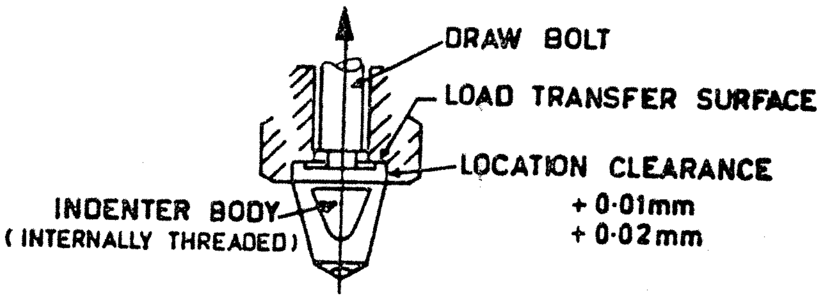
(g)



(h)



(i)



(j)

Fig. 27 (continued). Various methods of clamping indenters

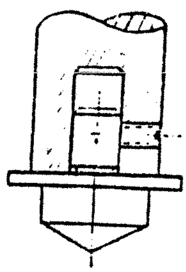


Fig. 28. The side tensioning screw

features of this machine are shown in Fig. 30. The weights and their knife edges are connected elastically. Indentation force is controlled, not indentation velocity. The accuracy of forces is stated to be within ± 0.1 %. The frame of the machine is designed so rigidly that no elastic residue can be recognized experimentally.

Before the advent of hardness standardizing machines the blocks were calibrated by commercial hardness testers of improved quality, constant maintenance being ensured by specially skilled personnel. In some laboratories such machines are still used as secondary standards for current calibration work beside the dead-weight primary standards [D-2]. The stability of the secondary standard is checked by daily comparisons with the dead-weight machine. The results are plotted in control charts. If confidence is built up, comparisons can be made less frequently, e.g. on a weekly basis. One could then say that the dead-weight standard is superfluous in such a case. This is not so. Stability and accuracy is ensured by the dead-weight primary standard. The lever type secondary standard serves only to reduce the work charge of the primary standard, and to reduce costs of block standardization.

The precision of indentation depth measurement on a commercial hardness tester used for block standardization was improved by replacing the dial gauge by a spiral microscope [Y-8]. In Italy a block manufacturer uses a lever type hardness secondary standard [B-12] for block calibration. Measurements are compared with those made on the dead-weight national standard.

The Japanese double-lever-type Brinell hardness standardizing machine is shown in Fig. 31 [S-11].

2. Indentation depth measurement on Rockwell hardness standardizing machines.

Most Rockwell standardizing machines used to employ a measuring microscope arranged according to Abbe's comparator principle for measuring indentation depth (Fig. 5). The essential of this principle is that the axis of microscope M is exactly perpendicular to the direction of displacement to be measured (in our case that of indenter S) and the graticule observed by the microscope is mounted in the geometrical axis of the indenter.

The various steps of Rockwell indentation measurement as seen in the microscope are shown on Fig. 32. With this type of microscope [S-7] the scale is displaced only for zero setting, afterwards it remains stationary, the double line b moves together with the indenter, while line c is displaced by the operator. Readings can be taken also after having removed the indenter.

Often two microscopes are mounted on a standardizing machine, permitting parallel measurement by two persons if increased precision is required (Fig. 6 and 33). Care should be taken that heat from the lamps a illuminating the graticule b shall not influence the accuracy of the latter. To this effect guiding the light of a lamp arranged at a certain distance by fibre optics was proposed in [K-2].

Measuring microscopes with a spiral head are frequently employed. The

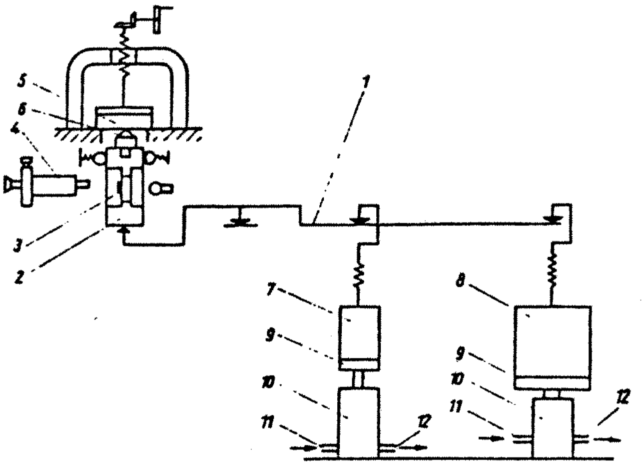


Fig. 29. Schematic diagram of the hardness standardizing machine of NRLM
1) Main lever 2) Rod
3) Graduated scale 4) Micrometer microscope 5) Standard block
6) Penetrator 7) Dead weight for preload 8) Dead weight for additional load 9) Table
10) Piston and cylinder 11) Oil pressure supply 12) Exhaust

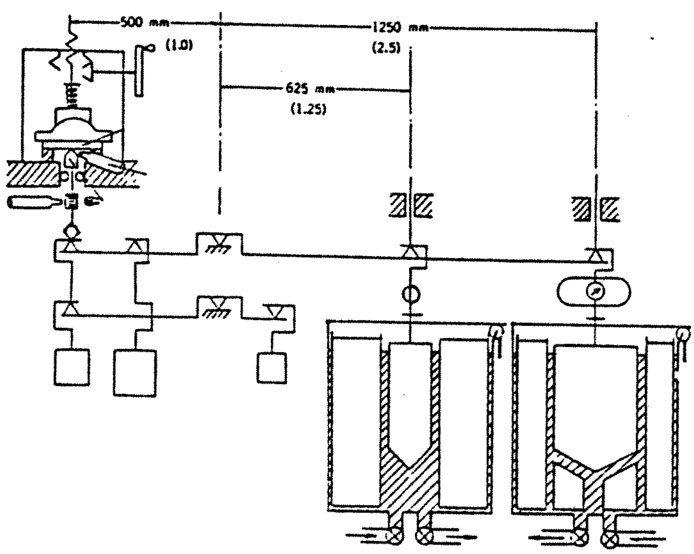


Fig. 30. Characteristic design elements of the machine shown in the schematic diagram Fig. 29

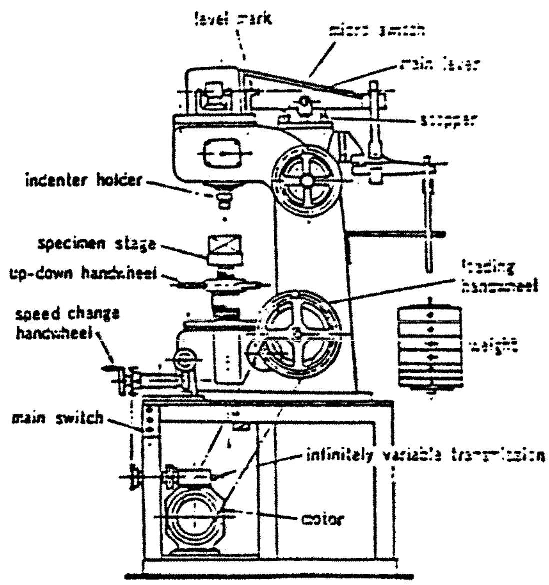
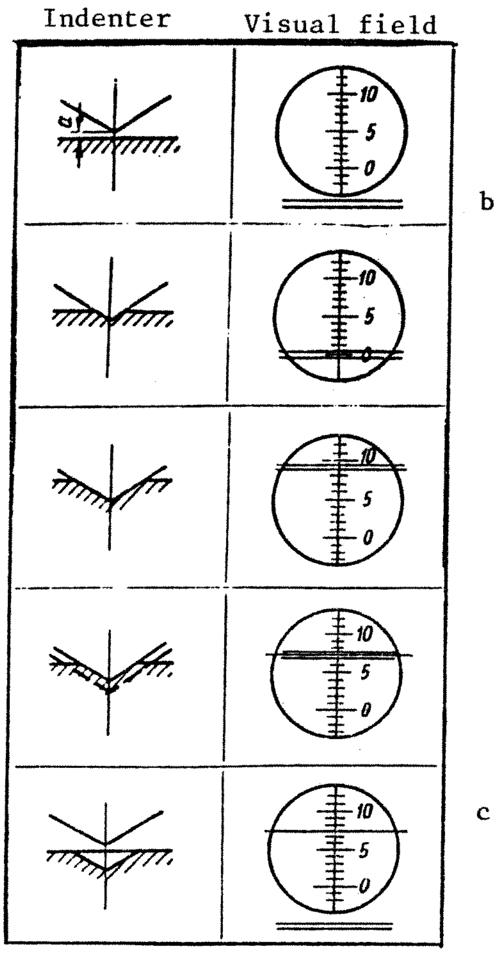


Fig. 31. Double-lever type Brinell standardizing machine



Before the cycle.

Preliminary force applied.
Zero setting of the microscope.

Total force applied.

Load reduced to preliminary force.
Reading of the microscope.

After the cycle.

Fig. 32. Steps of the indentation cycle, as seen on the microscope

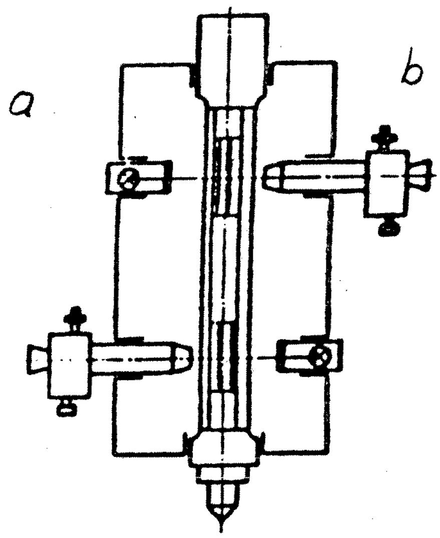


Fig. 33. Two microscopes arranged at two sides of the indenter shaft

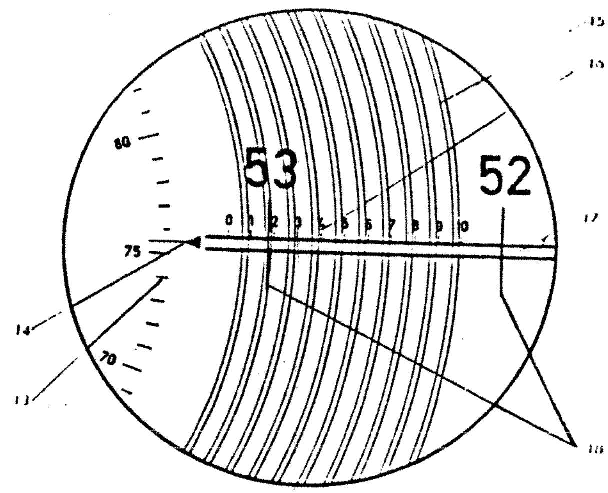


Fig. 34. Visual field of a spiral microscope (Zeiss)

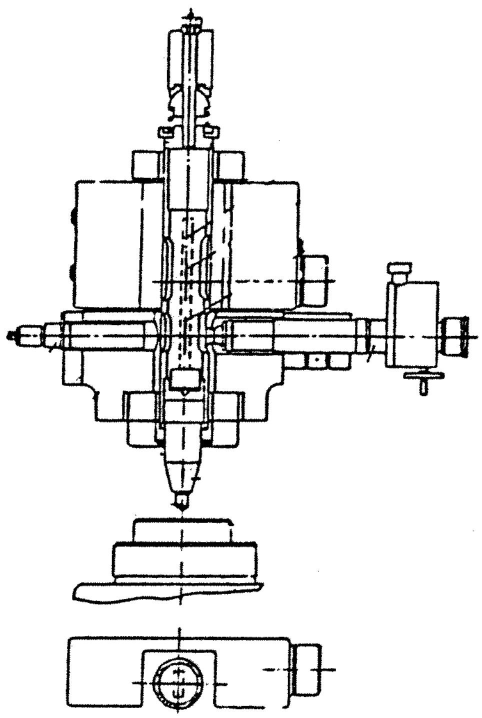


Fig. 35. Photoelectric grating counting device working in parallel with a spiral microscope

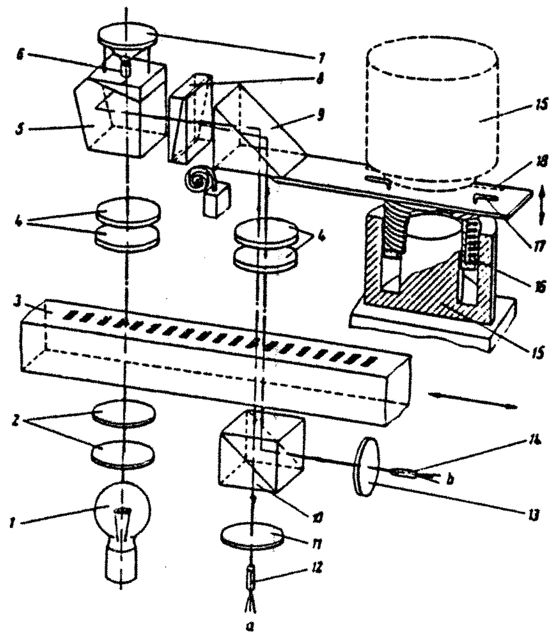


Fig. 36. Scheme of the photoelectric grating counting device

(3 grating, 8 Wollaston's prism, 6,12,14 phototransitors)

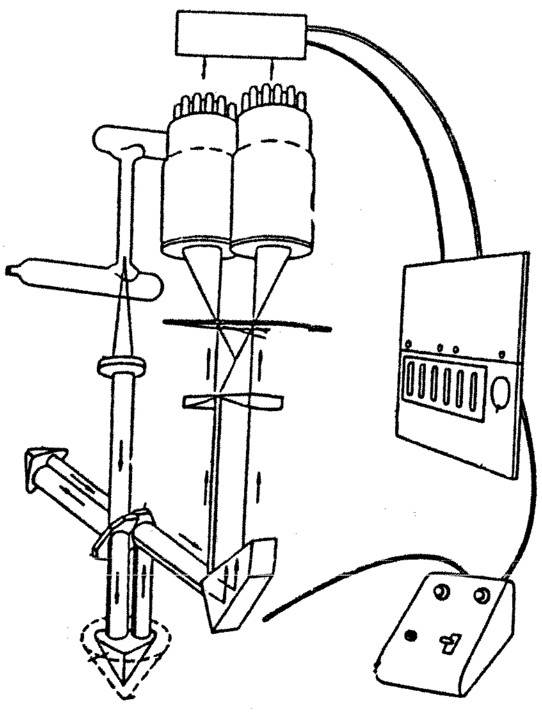


Fig. 37. Woodson interferometer for indentation depth measurement

visual field of a spiral microscope can be seen in Fig. 34. Lines 18 are moving with the indenter. The operator turns the screen on which spirals 15 and the micrometer graduation 13 are arranged. The figure shows the position of reading the value of 53.175 (5) mm. The line corresponding to 53 mm is brought by the operator between the double spirals. The tenths of a millimeter are read on the scale at 16, micrometers at 13. The tenths of a micrometer are estimated.

Measuring microscopes have some disadvantages which are especially apparent in the case of standardizing blocks in series. The manual setting of the instrument on two occasions during each indentation cycle is the source of personal errors which may increase with the fatigue of the operator. Measured values are to be noted and evaluated manually.

To improve the metrological characteristics of the depth measuring equipment, various other devices were employed on standardizing machines. The device shown in Fig. 35 and 36 can be mounted in parallel with the existing measuring microscope [M-16, M-21, M-25]. The lines of a grating moving with the indenter are counted photoelectrically and displayed in steps of 0.1 or 0.05 HRC (0.2 or 0.1 μm). Display values can be printed out, mean values, corrected values, standard deviations calculated.

Indentation depth is measured by a linear voltage differential transformer (LVDT) on the machine shown in Fig. 14 [D-2]. The coil of the transformer is arranged above the machine, on a separate frame. The difference between voltage outputs at the two positions of the indenter is automatically calculated and the Rockwell hardness number is displayed on the digital readout.

Another new method which is being increasingly employed in the last decade is the use of interferometers in Rockwell standardizing machines. A Woodson interferometer designed for indentation depth measurement [F-1] is shown in Fig. 37. A laser interferometer employed on the machine of Fig. 15 [B-1, B-2] can be seen in Fig. 38. The designer's aim was to separate in the machine structure the load carrying assemblies (black arrow heads) and the frame carrying the length measuring elements (clear arrow heads). The separation cannot be, of course, perfect. The layout of the optical components is shown at the right side of Fig. 38.

The plunger carrying the indenter and its guidings on the machine shown in Fig. 6, after rebuilding with a laser interferometer is shown in Fig. 39 [K-13]. The reconstruction necessitated a higher structure for the plunger carrying the indenter, with increased distance between bearings L_1 and L_2, what improved the guiding.

Due to the optical system employed here, a resolution of λ/16 was obtained with the laser interferometer. The microscope was nevertheless maintained as an alternative measuring method.

The optical system of the laser interferometer described in [M-25] is shown in Fig. 40. The resolution is λ/8, like on the machine described in [C-7].

A similar application of laser interferometer, on the machine shown in Fig. 18, is described in [T-4].

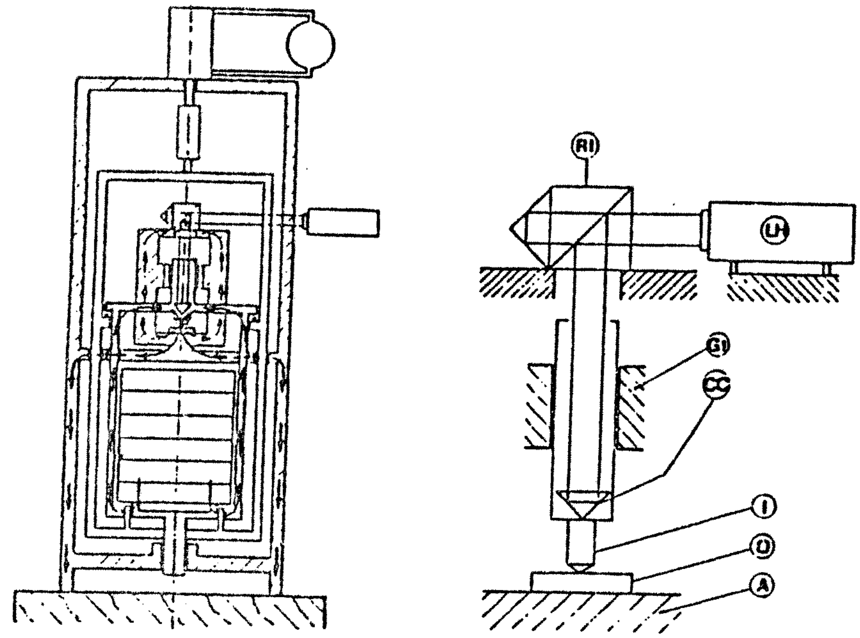


Fig. 38. Laser interferometer on the standardizing machine shown in Fig. 15
RI remote interferometer
LH laser head
CC corner cube

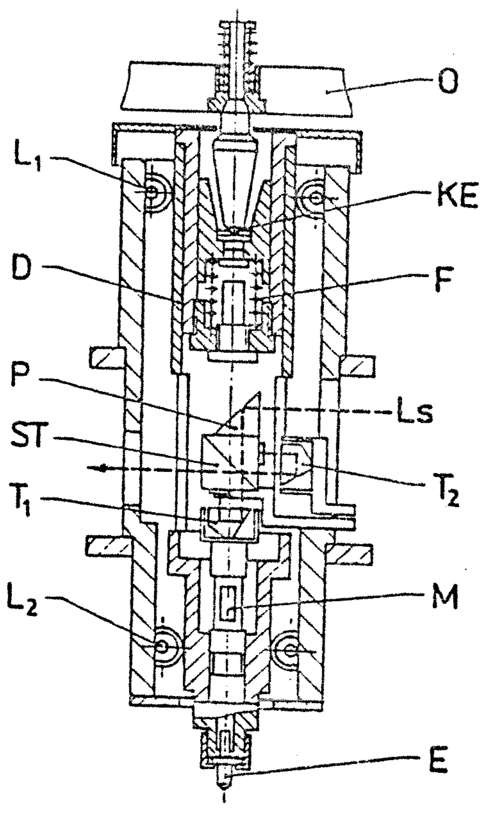


Fig. 39. Elements for depth measurement with laser interferometer on the machine shown in Fig. 6
Ls laser beam, P prism, ST beam splitting prism, T_1 moving corner cube, T_2 fixed corner cube, M graticule for the spiral microscope

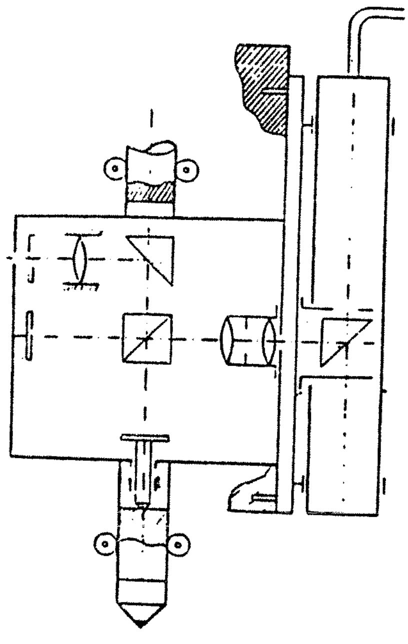


Fig. 40. Optical system of a laser interferometer for a Rockwell hardness standardizing machine (PKNJiM, Warsaw)

3. Measurement of Vickers and Brinell indentations

3.1. Microscopes

The diagonal or diameter of the indentation is measured on a microscope which is not united integrally with the Vickers and Brinell standardizing machine proper, and which is in many cases similar to microscopes used with commercial hardness testers. Measuring microscopes of micro-hardness testers are also used extensively for standardizing work.

The measurement of the diagonal or of the diameter of a hardness testing indentation is a length measuring problem in which, in most cases, the whole length to be measured is within the field of view of the microscope. The principle of a measuring microscope is shown in Fig. 41. The measured object is illuminated by a light source. The image of the indentation formed by the objective in the image plane is observed by the ocular, together with a moving graticule arranged in the image plane. As an example the design of a microscope built according to this principle is shown in Fig. 42.

The image of the Vickers indentation should be aligned in the centre of the field of view in such a way that the graticule moves in the direction of the measured diagonal. The lines of the graticule are set to the opposite corners of the indentation. To find the correct setting requires much skill from the operator, this is perhaps the most important source of errors. The most frequently occurring kinds of setting errors are shown in Fig. 43.The indentation diagonal is measured too short at a) and c). At c) the diagonal is not correctly aligned, but this is of lesser importance, being a cosine error.

The operating elements of the ocular of a microscope widely used in hardness standardizing practice is shown in Fig. 44.

By loosening knurled knob 1 the ocular can be rotated according to the direction of the indentation diagonal. Knobs 2 and 3 serve for the displacement of the image in two perpendicular directions. Setting of the line is made by turning the fine adjusting knob 6. An example of reading the diagonal length is shown in Fig. 44 b). The main division of the graticule represents an interval of 25 μm. The rest of the diagonal length, designated by a, can be read on the scale below the indentation.

Examples of other methods of diagonal measurement are shown in Fig. 45 [W-13, B-9, M-10]. In case a) the set line in the ocular is fixed, the image is displaced from position I to II by moving the table or the microscope tube. In case b) the set line is moved from position I to II. In case c) two systems of set lines are displaced. In case d) the image of the indentation is enclosed by two pairs of perpendicular lines, set to the sides of the indentation. In another desing solution (e) two pairs of perpendicular lines are set to the corners of the indentation.

To facilitate the correct setting of the lines on the corner of indentation, some microscopes employ dotted lines or doublet lines (Fig. 45 f). The opinions of specialists on design questions are often divergent, personal preferences or habits may have a role.

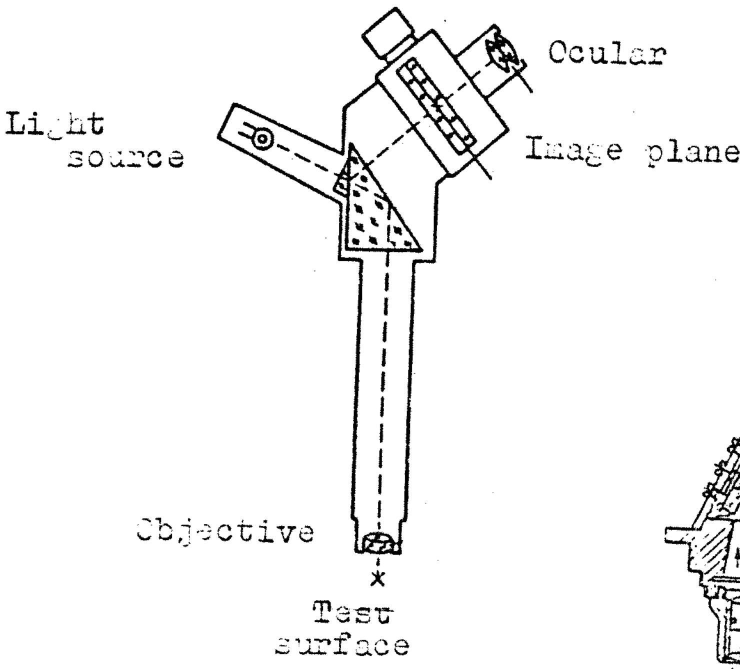


Fig. 41. Principle of a measuring microscope

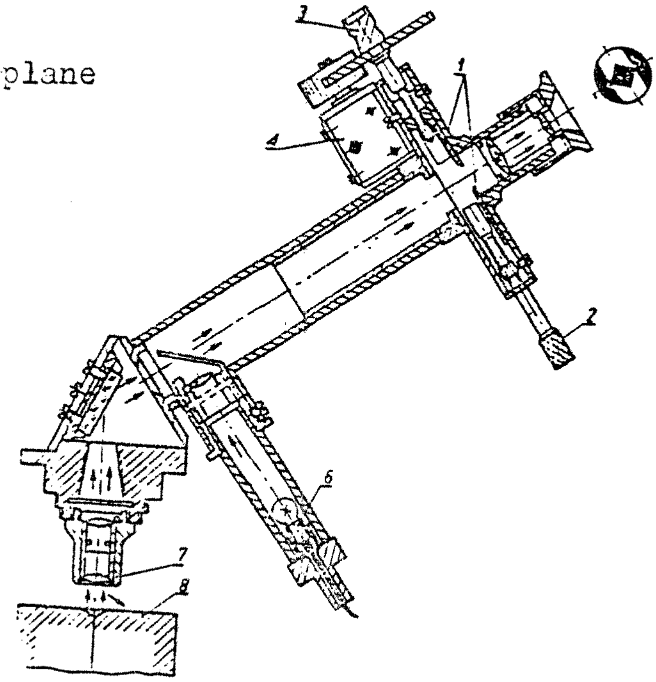


Fig. 42. Design scheme of a measuring microscope

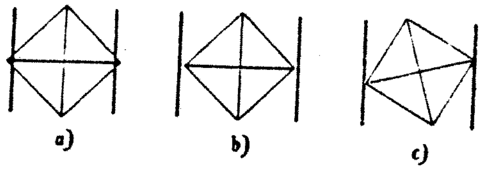


Fig. 43. Possible setting errors at measuring a Vickers indentation

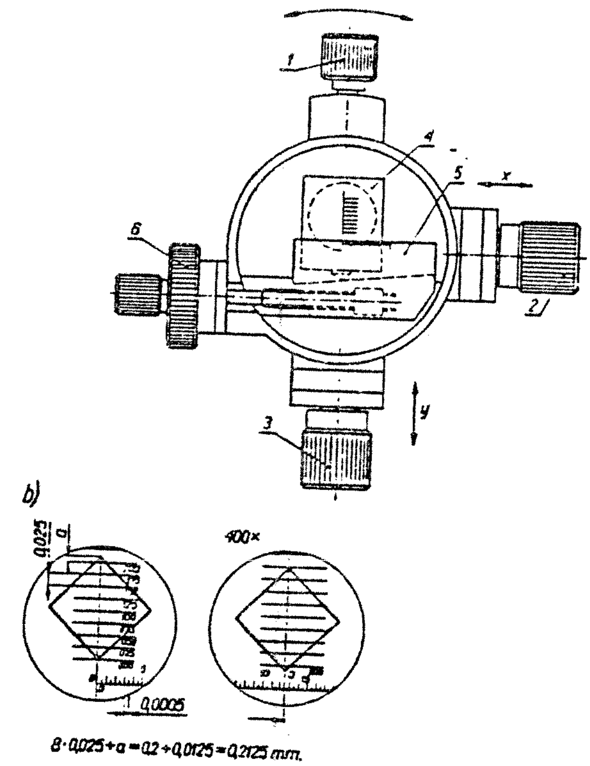
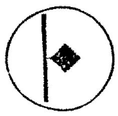
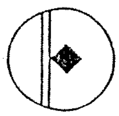
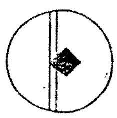
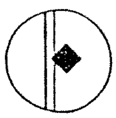
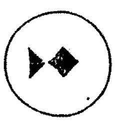


Fig. 44. Ocular of a Vickers measuring microscope (Leitz Durimet)

TANAKA and YANO [T-5] prepared a telescope type simulator to examine the errors of different persons when judging the coincidence of the corner of Vickers indentations with lines of various arrangements. The five line arrangements examined (denoted by P1 to P5), the short description of the method and some features are given in Table 2.

Table 2. Coincidence methods and its features

Method	Coincidence method	Features
P1 	Judgement is made at the point where the corner of a diagonally set square pattern comes into contact with reference line	This method has conventionally been used in Vickers hardness tests. In this method, the observer tends to feel as if the reference line and the corner of the pattern fused into each other
P2 	The method of coincidence is the same as that of P1	The reference line is made white and the observer is free from the feeling occuring in the above case
P3 	Judgement is made at the point where the corner of the pattern that has once appeared on the left side of the reference line has come to coincide with the left edge of the reference line by moving towards the right	To the observer, this method is easier than the methods of P1 and P2 in making a judgement
P4 	Judgement is made at the point where the corner of the pattern has just reached the centre line between two reference lines	Since the corner of the pattern is in the open space, it can be free from the effect to the reference lines
P5 	Judgement is made at the point where the corner of the target having similar form to that of the pattern and the corner of pattern have just met each other	The corners of the patterns to meet each other are symmetrical

The analysis of variance of repeated measurements with several observers showed method P3 to be significantly better than any of the others.

The double-line system (P4) is widely used in length measuring practice, where the reference is the centre of the transparent portion between two black parallel lines. In hardness measurements [B-13] the asymmetry of the end portion of an indentation offsets its well known advantages.

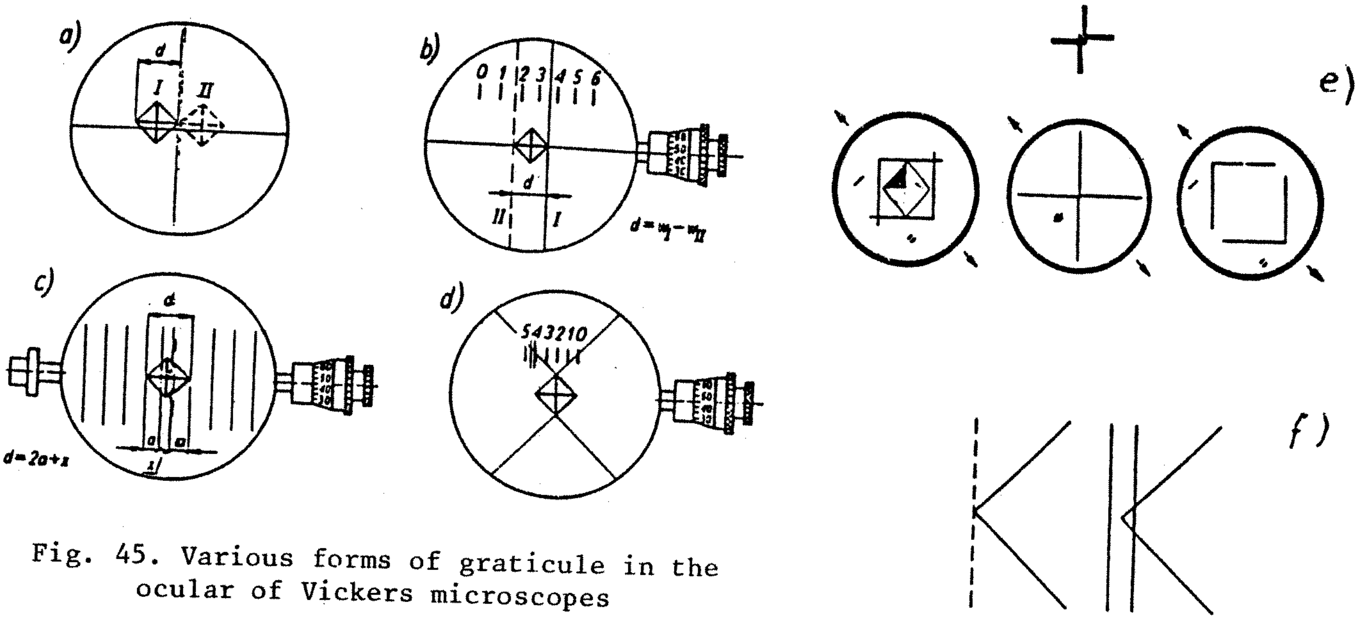


Fig. 45. Various forms of graticule in the ocular of Vickers microscopes

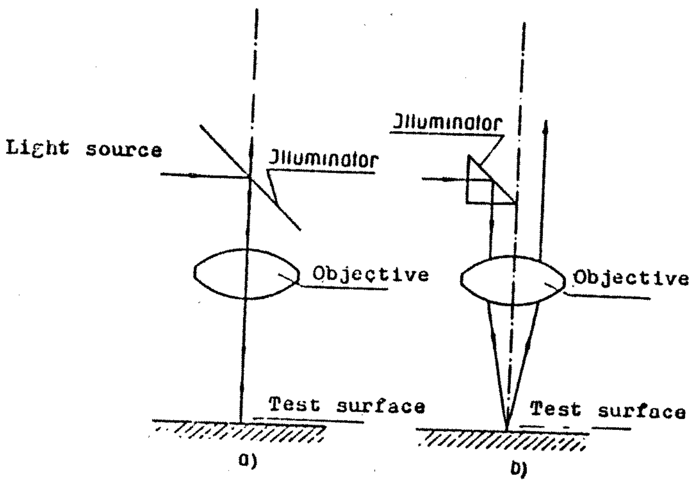


Fig. 46. Bright field illumination

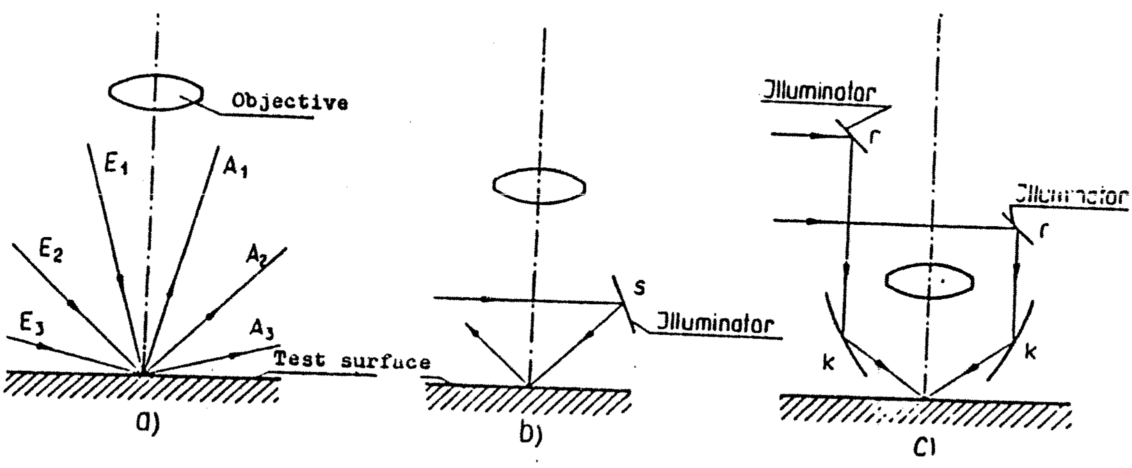


Fig. 47. Dark field illumination

BARBATO [B-13] examined the conditions of collimation of the image of the indentation and of the reference mark. The operator's errors are the result of physio-psychological processes, which are however of constant characteristic, at least on short term. Since indentations do not possess any characteristic well defined points whose observation may be made any sharper by increased resolution of the microscope, the operator's resolution capability plays an important role, especially in detecting images with dimensions tending to zero at the most interesting points (corner of the Vickers indentation). At the same time the accompanying physio-psychological processes of image recognition are fundamental for the "creation", as we may well call it, of collimation points that do not exist in the optical image.

This short discussion of the measurement process already shows numerous error sources at determining the length of an identation diagonal or diameter. Four settings of the line are necessary for each indentation, with four readings of the dial. The uncertainty of setting the lines to the corners or circumference of the identation, the subjective differences in judging their position are sources of systematic and random errors, which will be discussed later.

The main problem is [B-13] that indentation boundary lines are not so sharply defined as a change from the black to the white observable on microscopes. This underlines the paramount importance of properties of the optical system used for indentation illumination and observation, since it "creates", not only magnifies the image that will be considered the measurand.

In the following some aspects of the suitable selection of microscope characteristics are discussed.

3.2. Some influence factors at measurements by the microscope

3.2.1 Illumination

The importance of the illuminating system cannot be over-emphasized as the object to be measured is non planar, consequently the nature of the illuminating beam of light can radically alter the apparent size of an indentation. [W-18, W-19]. A maximum contrast is required between the surface of the test block and the image of the indentation. In addition the edges of the indentation must be sharply defined.

A very strong illumination may be rather disturbing in the case of highly polished surfaces. Yellow-green light is more pleasant for the eye.

One possible classification of illumination systems distinguishes bright and dark field systems. With bright field illumination (Fig. 46) [M-13] the light arrives onto the tested surface through the objective of the microscope. Being reflected from the tested surface, the light re-enters the objective and the tube of the microscope. If a part of the reflecting surface is not plane (e.g. it carries an indentation), those light beams which are reflected by the indentation do not re-enter the objective, the indentation appears dark against the bright surfaces not altered by the indentation. Most measuring microscopes employ bright field illumination.

Optical systems for dark field illumination are shown in Fig. 47. Illuminating light beams (E) reach the tested surface from around the objective, thus they pass outside the objective after reflection by the plane surface. If the surface carries an indentation, some of the reflected beams enter the objective. Thus a bright image can be observed in the ocular against a dark surface of the test piece.

MEYER [M-13] suggested dark field illumination for Brinell indentations up to a magnification of 11x. For higher magnifications bright field illumination is preferable. At measuring Vickers indentations bright or dark field illumination are equally suited.

The effect of illumination was examined also by WEINGRABER [W-13], based on earlier work by O'NEILL, ESSER, CORNELIUS and SPORKERT. The adjustment of the aperture of the illuminating system has conventionally been employed. But it is known that systematic error of the measured value in such cases depends on the individual observers, since there is no optimum aperture for all observers [T-5].

In view of the experimentally proved sensitivity of measuring microscopes to illumintion, the ASTM Test Method for microhardness testing [SR-54] gives detailed instructions for the adjustment of illumination :

- Proper illumination is necessary in order to obtain optimum resolution from a microscope. There are two systems which give proper illumination. Abbé-Nelson or "critical" is the system in which the image of the illuminating source is focused in the plane of the specimen. Kohler illumination is the system in which the illuminating source is imaged at the rear focal plane of the objective lens.

  While some optical systems are permanently aligned, others have means of minor adjustments. To gain the utmost in resolution the operator should make the following adjustments :

  Abbé-Nelson Illumination :

  - Focus to critical sharpness the surface of a flat polished specimen.
  - Center the illumination source.
  - Centrally align the field and aperture diaphragms.
  - Adjust the lamp so that the filament is in sharp focus in the specimen plane.
  - Close the field diaphragm so that a thin, dark ring rims the field of view.
  - Close the aperture diaphragm until the glare just disappears. Never close the diaphragm to the point where diffraction phenomena appear.
  - Place a diffusing disk in back of the field diaphragm if the lamp is not a ribbon-filament type.
  - If the light is too strong for eye comfort, reduce the intensity by the use of an appropriate neutral density filter or rheostat control.

Kohler Illumination :

- Focus to critical sharpness the surface of a flat polished specimen.
- Center the illuminating source.
- Centrally align field and aperture diaphragms.
- Open the field diaphragm so that it just disappears from the field of view.
- Remove the eyepiece and examine the rear focal plane of the objective. If all the components are in their proper places, the source of illumination and the aperture diaphragm will appear in sharp focus.
- Full-aperture diaphragm is preferred for maximum resolving power. If glare is excessive, reduce the aperture ; but never use less than the 3/4 opening since resolution would be decreased and diffraction phenomena could lead to false measurements.
- If the light is too strong for eye comfort, reduce the intensity by the use of an appropriate neutral density filter or rheostat control.

Illumination may be modified also by the surface quality of the measured hardness test block. Surface polish may influence the setting of the graticule to the corners of the indentation.

Image contrast is not easily controlled in optical systems [B-13]. Image contrast level depends, among others, on internal reflections and on the quality of antireflection treatments. Manufacturers tend to increase both resolution and contrast in their instruments, though these two conditions appear to be antithetical.

In practice, everything is entrusted to the regulation of light, which, in the case of indentations, may lessen contrast. Luminosity should be regulated according to the personal requirements of the operator, so as to ensure the best use of the optical system.

3.2.2. Optical configuration

The design of the objective may also influence the uncertainty of measurement [O-1, I-3]. E.g. with telecentric objectives the influence of not perfectly correct sharp setting on magnification is less important.

3.2.3. Resolving power, aperture, and magnification ratio

The resolving power of a Vickers measuring microscope in function of numerical aperture is shown in Fig. 48 [M-12]. In commercial measuring microscopes objectives of 40X magnification with numerical aperture values from 0.45 to 0.70 are available. The corresponding resolving powers, according to the figure, are 0.6 and 0.4 µm, respectively. At measuring microhardness indentations with such objectives, the difference of 0.2µm in resolving power may have a significant influence on the measured value. At comparing values obtained with objectives of different numerical apertures, this fact should be taken into consideration, in the case of small indentations.

High magnification ratio can reduce errors of setting the lines correctly to the indentation, but at the same time image quality may be deteriorated. A reasonable compromise should be found. It is convenient if the diagonal or diameter of the indentation corresponds to 1/3 to 2/3 of the diameter of the field of view of the microscope.

ILLIG [I-4] suggests that the product of the dimension of the indentation (in mm) and of magnification should be at least 50. The corresponding magnification ratios in function of indentations are given in the following table :

Diameter or diagonal, mm	magnification
5 - 15	10 x
3.2-9.0	16 x
2 - 6	25 x
1.25-3.75	40 x
0.8-2.4	63 x
0.5-1.5	100 x
0.32-0.9	160 x
0.2-0.6	250 x
0.12-0.37	400 x

ČUTKA (C-2) examined the stability of the magnification ratio of two microscopes in time. Checking was made by the help of a stage micrometer. In four years, one microscope changed by 0.15 %, the other 0.3 %. In the latter case the illumination lamp was repeatedly,exchanged.

3.2.4. Standard microscope ?

Standard specifications give very few information on the optical characteristics of the microscopes used for indentation measurement, what implies an incomplete knowledge of the phenomena involved in the measurement process [B-13]. Many specialists are of the opinion that international unification of Vickers and Brinell hardness scales would be greatly facilitated if the optical characteristics of measuring microscopes were unified, i.e. all the standardizing laboratories were using similar microscopes. One must be, however, aware that the realization of this justified desire is not probable in the near future.

3.3. Development trends

As discussed earlier and evidenced by experimental values cited later in connection with the discussion of uncertainties, the measurement of Vickers and Brinell indentations on a microscope is a tiresome work burdened with several error sources. It is desirable to eliminate personal effects as far as possible and to reduce the intrinsic limititations of the measurement methods. Development work is going on in various directions, some of the solutions to be discussed briefly are still at the stage of elaboration, it is difficult to judge now, which of them will fulfil all the hopes.

Proposed new measurement methods can be classed into two main groups :

- By maintaining the classical method of adjusting the lines of the microscope to the corners or edges of the indentation by a manual

operation, the evaluation of the position of the lines is automated.
- To eliminate the very subjective judgement of the position of the corner of the indentation (i.e. of the length of the indentation diagonal), the whole evaluation of the area of indentation is performed independently of the length of the diagonals or diameters.

Among innovations belonging to the first group we may mention the oculars with digital indication of the measured value [M-10]. This permits also a computer and printer connection, producing an output in hardness value. In this way, the series of operations of microscope measurements, namely setting-reading-calculation, is reduced to the first operation, the others are performed automatically.

Several experimental and already commercialised apparatuses with optical-electronic detection and television cameras, belonging to the second group of developments, were described in the technical literature:

3.3.1. A new apparatus for measuring Vickers identations utilizing the photoelectric detection was developed by KOIZUMI [K-7]. Two measuring methods were employed. The first is the detection of the relative position of the corners of an indentation by the ratio output of photomultipliers in a photoelectric microscope. With the second method the position of the edges of the indentation is detected. Standard deviation of diagonal length values obtained are of the order of ± 0.1 µm.

3.3.2. For the measurement of very small Vickers indentations (10 to 70 µm diagonal length) a photometric measuring method and apparatus has been developed by REINIGER [R-8, -9, -10]. Uncertainty is less than ± 2 % of length.

3.3.3. In an effort to make Vickers indentation measurements free of personal effect, BARBATO [B-10] studied the possibility of obtaining the image of the indentation by a TV camera, which is then digitized, in order to determine its contour by numerical techniques. The observed area was recorded into a 512 line, 512 column matrix. Actual resolution is higher than 1/512 of the field of view of the vidicon. The first application concerns mostly the microhardness range. The method still involves a subjective factor, namely the focusing of the indentation image, which may be done differently by different persons. A future step will be focus adjustment without observing the image, by simply bringing the contrast level to the maximum.

The replacement of measuring microscopes by automatic equipment is technically mature. There exist numerous instruments for other applications with which the area of very complex surfaces can be determined. BARBATO et al. [B-17] developed a system for indentation image analysis, with which both image area and diagonals can be determined. It is well known that the subjective error of microscope operators is due to the different ways of extrapolating indentation sides to define a vertex that actually does not exist. Therefore an automatic extrapolation, namely the definition of the vertex position by a mathetical algorithm is more advisable, than the increase of the resolution of the instrument, if uncertainty is to be reduced. Ressort had therefore to be made to a sophisticated procedure for image analysis, based on successive phases : contour detection, vertex recognition, and dimension measurement. In actual realization, this measurement system, like the ordinary industrial systems, uses a microscope, a telecamera, and a system for image processing, but it is additionally equipped with a translation slide having a motion resolution of 0.1 µm and with a laser system for translation measurement. The measurement of all the indentations is made with a 50x lens of NA 0.5, which is the maximum usable for indentation observation. This is possible because it is not necessary to observe the whole indentation, but only one vertex at a time.

The difference between diagonal measurements repeated in a short time interval was of the order of 0.1 µm ($\approx 2\ \sigma$). The method is suitable to realize a primary Vickers hardness reference. Nevertheless, since there is no natural hardness standard serving as the basis of traceability, one cannot exclude systematic errors. One of the characteristics of this image-analysis system is the attempt at reproducing the physio-psychological behaviour of human vision, consequently the repeatibility, reproducibility and stability of Vickers hardness measurement is considerably improved.

3.3.4. Another automated measuring system functioning with a television camera was described by VOLLATH and SIEMER [V-2]. The image of the indentation is recorded by a television camera attached to the microscope and fed to the image processing system for evaluation. Prior to the measurement magnification, illumination and focusing are automatically adjusted by the image processing system to allow the television camera to operate under optimum conditions. In the next step, the analog half-tone picture recorded by the camera must be converted into a digital binary picture in which the measurements will be made. For this segmentation the "shadow boundary" of the hardness indentation must be found. The shadow boundary is determined automatically before each measurement. After the shadow boundary has been found and the respective binary image has been loaded into the image processing computer, the corner points are determined with an algorithm. This works without any problems as long as the specimen has been prepared according to standards. In the majority of cases also hardness indentations can be measured whose specimen surfaces are in a much poorer condition. If no clear corner points can be found, this process is repeated after "image cleaning".

The technique can be used, with minor modifications, also for automated measurements of Brinell hardness indentations. Accuracy requirements for hardness testing in industrial laboratories (not standardizing work) can already be satisfied.

3.3.5. An optoelectronic measuring system with similar claimed resolution and accuracy was described by SACK [S-17, W-26]. A semiconductor camera with matrix-shaped arrangement of the photosensitive elements is used as transducer. The measuring range covers diagonal lengths of 5 to 300 µm. Image processing is performed automatically in a computer. The image is digitized prior to processing. Image processing serves to eliminate optical interference and to edit the raw data.

3.3.6. The automatic measurement system AAV used in Japan for the calibration of Vickers blocks (Y-22) is functioning since 1986 already in its third version. An improvement in comparison with former versions is the use of a CCD camera for pick up, with about 500 elements. The objectives have magnifications of 5x, 10x, 20x, 40x, 100x. The first is suited for the measurement of diagonals in the range of 60 to 400 μm, while the last one for 3 to 20 μm. The principle of functioning can be seen in Fig. 49. When passing along the direction of the diagonal of the indentation, brightness abruptly falls as we reach the dark indentation. Of course the fall is not like a step function shown below the indentation. The encercled corner of the diagram is shown enlarged under (c). To find the correct threshold, a calibration of the system by means of an optical micrometer is necessary, shown under (b).

3.3.7. A not optical method for measuring Vickers indentations was examined by EYERER and LANG [E-3]. The profile of the indentation was traced by the stylus of a surface roughness tracing instrument. Up to diagonal lengths of 50 μm satisfactory agreement with optical methods was obtained.

3.3.8. BÜCKLE [B-7] employed a photographic evaluation method. The indentation is photographed, the image united with that of a graticule. Evaluation is then made visually. The method can be advantageously employed for the evaluation of a high number of very small microhardness indentations (3-30 μm).

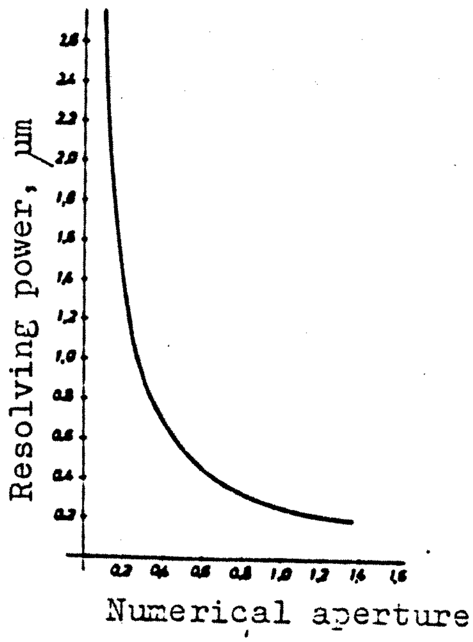


Fig. 48. Resolving power in function of numerical aperture

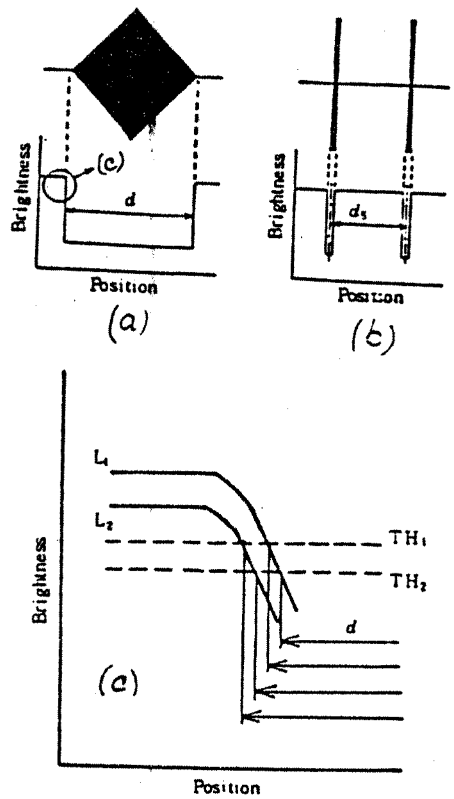


Fig. 49. Principle of the automatic measurement of a Vickers indentation (a). Calibration by means of an optical micrometer (b)

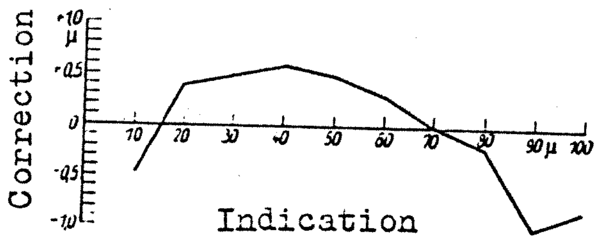


Fig. 50. Error curve of a microscope during one turn of the spiral

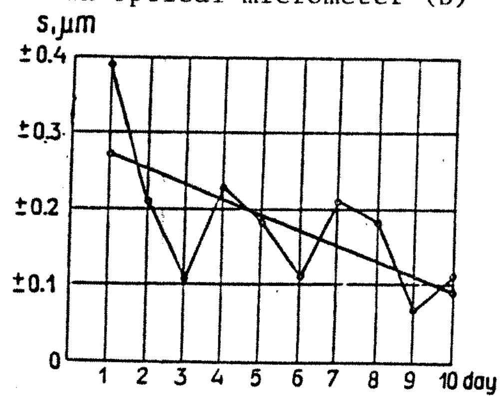


Fig. 51. Daily variations of the standard deviation of one of the observers at setting the spiral microscope

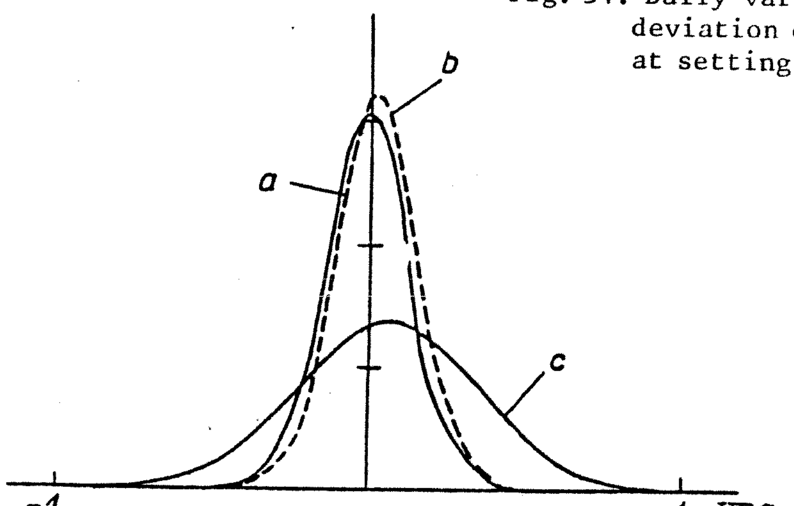


Fig. 52. Frequency diagram of the differences of two observers

PART II. MEASUREMENT UNCERTAINTY

4. Uncertainty of Rockwell indentation depth measurement

4.1. Specified requirements

OIML International Recommendation No. 12 [SR-25] and ISO Standard 674-1988 [SR-15] specify that "the measuring device shall be capable of measuring vertical displacements within ± 0.1 of a scale unit.

According to ASMW-VM145 [SR-51] the maximum permissible error of the depth measuring equipment on a Rockwell hardness standardizing machine, as determined at a length of 200 or 100 µm, should be :

± 5 x 10^{-4} if the scale interval is 0.5 µm or less
± 1 x 10^{-3} if the scale interval is 1 µm

To check this value according to [SR-51] a dummy indenter should be clamped into the machine. Gauge blocks of 1.0 and 1.2 mm length (1.0 and 1.1 for Rockwell superficial tests) should be measured alternately by the dummy indenter under the preliminary test load, 13 times. Of the resulting 12 depth difference values the mean value and the standard deviation is calculated.

According to the Japanese prescription [SR-53] for block calibrating machines (especially lever type) the error of the indicating apparatus should be within ± 0.3 HR (and ± 0.6 HR for Rockwell Superficial). These values, which correspond to ± 0.6 µm, are specified for the mean of 3 measurements. The dispersion of values, i.e. maximum minus minimum should not exceed 0.6 µm.

4.2. Systematic errors of spiral microscopes

The spiral microscope may have a periodical systematic error at turning the spiral. A sinusoidal error curve plotted by FLURSCHÜTZ [F-1] is shown in Fig. 50. This is in conformity with the error stated by the manufacturer : "Inaccuracy of the instrument ± 0.5 µm at the maximum".

ČUTKA [C-1] describes an examination of the microscopes of four standardizing machines. The employed method was similar to that given in [SR-51], but several gauge block combinations were used, giving depth differences from 0 to 1 mm. In the range of 0-30 µm, which is of interest at Rockwell tests, the systematic error never exceeded ± 0.1 µm. Nevertheless the same publication describes the experiments to establish the correction values for three secondary hardness standardizing machines. The correction values were determined for both microscopes arranged on the same machine. Differences between the two microscopes were up to 0.2 HRC (≈ 0.4 µm).

WEILER, HILD and GEBHARDT [W-11] prepared a test assembly permitting to plot the correction curve of spiral microscopes. The systematic errors of seven microscopes were found to be between + 1.0 and - 0.5 µm, if measuring a length of 200 µm. Systematic differences of two microscopes working in parallel were also examined [W-10].

4.3. Random uncertainty of spiral oculars

Experiments were performed on measuring microscopes with spiral oculars [P-3] to determine the magnitude of the most important component factor of the error of depth measurement, namely the uncertainty of spiral setting. On the spiral microscope the line is to be brought between the two concentric spirals in the ocular, by means of rotating the setting knob. This setting, of the spirals is burdened with a certain degree of uncertainty. To determine the precision of setting, the indenter was replaced by a dummy indenter having a flat lower (contact) surface. Thus a stable position of the indenter holding shaft and of the scale mounted thereon was ensured when the preliminary force was applied. Two observers measured then the position of the scale line ten times in a sequence, on the two microscopes simultaneously. Afterwards they changed positions at the microscopes and made another ten measurements. This process was hereafter repeated by another couple of observers. The four observers performed this same series of measurements on ten days. The data of 200 spiral settings for each of four observers, being of various ages and having various degrees of practice in this kind of work, were finally evaluated as follows :

a) The mean standard deviation for the four observers was $s = \pm 0.22$ µm.
b) There was no significant difference between the individual observers, the best value being ± 0.20, while the worst ± 0.23 µm.
c) There was no significant difference between the results obtained on the two microscopes.
d) The standard deviation of each observer showed a considerable daily variation, nevertheless it was slightly improving with time during the 10 days of the experiment. The values for one of the observers, with the regression line constructed on the basis of least squares are shown in Fig. 51.
e) The reliability of an observer can be characterized by the daily variations of his standard deviation. There was no significant difference between the four observers in this respect. It is interesting to mention, however, that the observer producing the lowest mean standard deviation had the highest daily variation, while the one with the highest value had very small variations from one day to another.
f) The same experiment was repeated some years later, after maintenance work on the microscopes, with two new observers [P-20]. Their standard deviation values were found to be ± 0.19 and ± 0.15µm, respectively. This is a significant improvement with respect to values given under a). These values are in conformity with data of the manufacturer, specifying ± 0.25 µm as the uncertainty of spiral setting.

The measurement of an indentation depth requires two spiral settings and readings. Accordingly the value of $s = \pm 0.22$ µm mentioned under a) should be multiplied by $\sqrt{2}$ to obtain the component of the uncertainty of depth measurement resulting of ocular adjustment :

$$s' = \pm \sqrt{2} \times 0.22 = \pm 0.31 \ \mu m$$

In a similar experiment [K-2] the standard deviation of ten spiral settings was found to be ± 0.074 µm. By replacing the microscope by another, having scale intervals of 0.1 μm, standard deviation was reduced to ± 0.032 μm.

The three persons participating in this experiment had personal bias values. They adjusted the two microscopes to values being in a range of ± 0.2 and ± 0.05 μm, respectively, around the mean of the three persons.

4.4. Random uncertainty determined from parallel measurements

If two microscopes are used for measuring indentation depth in parallel, the evaluation of the differences between the two observes also permits an evaluation of random uncertainty [C-1, P-4]. Fig. 52 shows the distribution of the differences of values determined by two observers. Curve a represents the differences in a series of 525 indentations, curve b that of 1 700 indentstions. Curve c shows the results of two observers with little experience. The standard deviation of differences in the case of curve a is ± 0.13 HRC.

Supposing that the uncertainties of observers A and B do not differ significantly, i.e.

$$s_A \approx s_B ,$$

then

$$s_A^2 + s_B^2 = 0.13^2$$

and

$$s_A \approx s_B = 0.09 \text{ HRC}$$

what is the standard deviation of one depth measurement.

4.5. Random uncertainty determined by measuring a height difference

By employing the method of measuring the height of two gauge blocks [SR-51] KERSTEN [K-2] found standard deviation values of ± 0.11 μm. In a similar experiment [P-20] the values obtained by the experienced observer were ± 0.09 to ± 0.13 μm, while those of the less experienced observer working in parallel ranged from ± 0.17 to ± 0.24 μm.

To summarize random uncertainty values for indentation depth measurement, determined by the different methods discussed here, Fig. 53 was constructed. Values for the standard deviation of spiral setting were multiplied by 1.41 to consider the fact that a depth measurement implies two spiral settings. In this way data are compatible with those of the other two methods.

4.6. Further experiments to determine components of uncertainty

Part of the uncertainty of microscope reading originates from the interpolation of the position of the reference line between scale marks. ČUTKA [C-1] evaluated the frequency of interpolated decimal values for more than 3 000 measurements made by two observers. The results are shown in Fig. 54. The scale interval was 1 μm, the interval was subdivided by estimation to 0.1 μm. The small circles connected by the

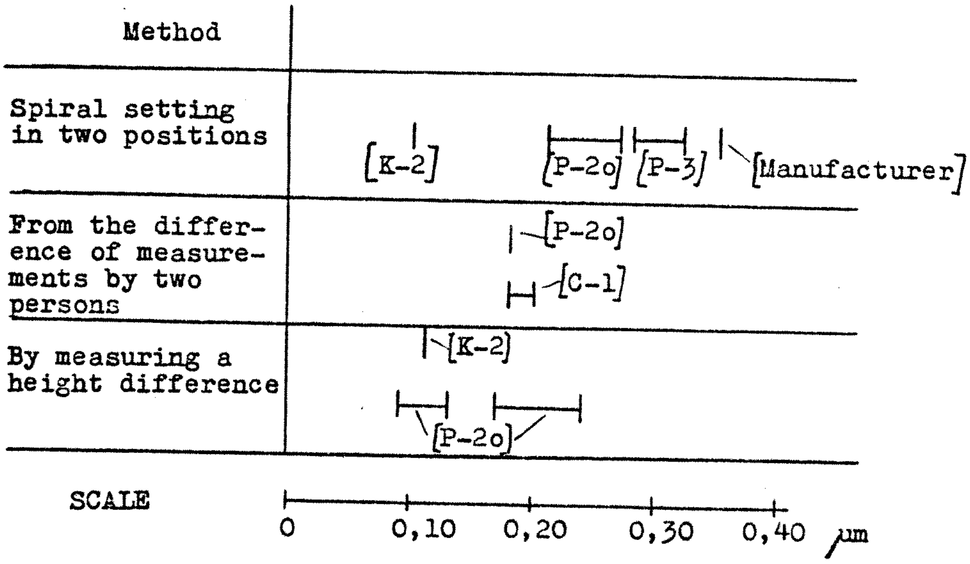


Fig. 53. Comparison of published standard deviation values characterizing indentation depth measurement by a spiral microscope

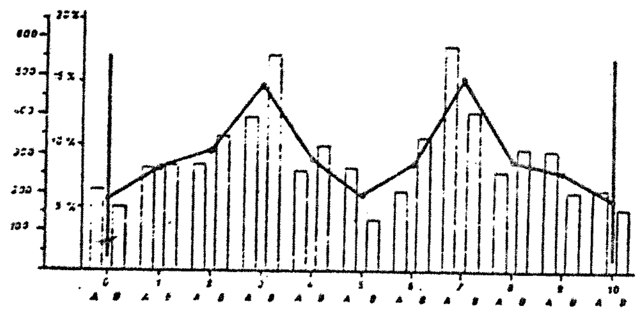


Fig. 54. Frequency of estimation of decimal values between two scale marks

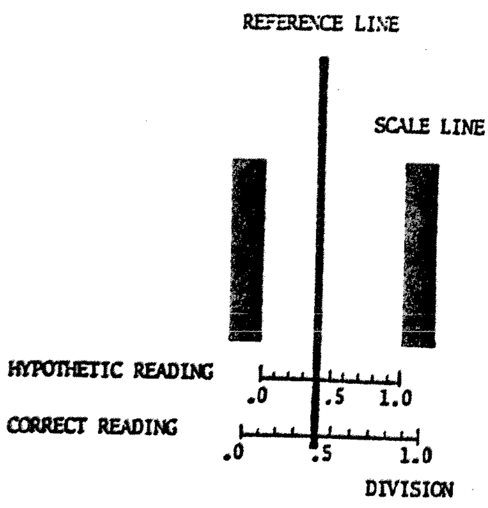


Fig. 55. Incorrect interpolation between thick scale lines

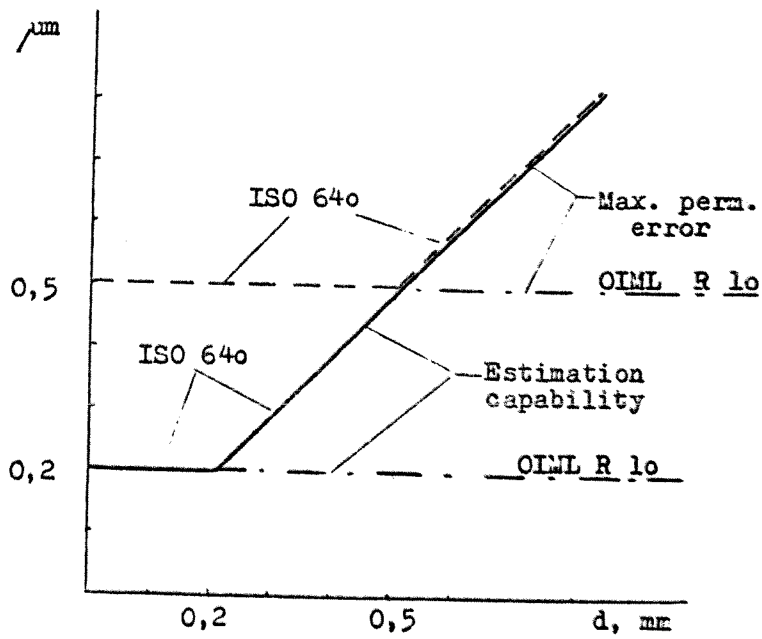


Fig. 56. Maximum permissible error and estimation capability of the measuring microscope according to ISO and OIML documents

strong lines represent the average of two observers. The values of each observer are shown by the columns. The most preferred decimals interpolated by both observers were 0.3 and 0.7 while 0.0 and 0.5 occured with the lowest frequency. Even 0.1 and 0.9 µm were given more frequently than the whole µm values, represented in the figure by the scale marks.

TANAKA [T-5] examined the interpolation errors in the case of thick scale lines. Observers were generally inclined to interpolate only the distance between the edges of the two scale lines, in place of the distance between the axis of the two scale lines (Fig. 55).

Another personal influence factor should be still mentioned. Let us take the example of measuring the hardness 61.4 HRC. The measurement can be carried out in two ways. The first method : After having applied the preliminary force, the microscope is zeroed. At the second reading we read on the microscope 77.2 µm. The second method : Under preliminary force we read the indication, e.g. 12.7 µm. In this case the second reading will be 89.9 µm. Indentation depth is obtained by the substraction 89.9-12.7 = 77.2 µm. This second method is recommended. At employing the first method for repeated measurements, the operator may remember the previous reading on the same block and his interpolation may be influenced by the former value. This is not the case with the second method. The little extra work of making the calculations after having measured all the indentations on the same block helps to obtain uninfluenced data.

Some other data on microscope uncertainty were published in the literature :

YAMAMOTO [Y-6] employed a micrometer microscope having an accuracy of 0.3 µm (maximum, limit error). SMOLITCH [S-7] mentions that the error of the observer was less than 0.2 µm.

4.7. Uncertainty of new depth measuring means

KERSTEN [P-17] gives the uncertainty of the spiral microscope as $u \leq \pm 0.14$ µm, that of an improved microscope as $u \leq \pm 0.07$ µm, where u denotes the confidence limit for n = 25 measurements and a probability of P = 0.99. The corresponding value for the He-Ne-Laser interferometer was found to be $u \leq \pm 0.023$ µm, corresponding to a reproduction of the Rockwell scale within 0.012 HRC [K-13].

A similar improvement of measurement characteristics was observed by ČUTKA [C-1, C-7]. With the spiral microscope the error limit for the measurement of a single indentation was ± 0.25 HRC, what corresponds to ± 0.08 HRC in the case of 10 measurements. The corresponding values for the laser interferometer were ±0.06 and ± 0.02 HRC, respectively.

BARBATO [B-1, B-2] found that the laser interferometer has a sensibility of 0.01 µm and a mechanical stability of 0.01 µm.

The accuracy of the photoelectric grating counting device (Fig. 36) is stated by MIKOSZEWSKI [M-21] to be better than ± 0.1 HRC. Depth measurements made by the linear voltage differential transformer (Fig. 14) [DE BELLIS, D-2] are accurate to 0.1 µm.

5. Uncertainty of Vickers indentation diagonal measurement

5.1. Classification of errors

Errors influencing the measured diagonal value can be classified as follows :

a) Systematic errors
  aa) Instrumental
  ab) Personal

b) Random errors
  ba) Instrumental
  bb) Personal

5.2. Specified requirements

The International Standard ISO 640-1984 [SR-17] contains the following requirements for the measuring microscope used for the standardization of Vickers hardness test blocks :

The scale of the measuring microscope shall be graduated to permit subdivision for estimation of the diagonals of the indentation to within 0.1 % of d for d > 0.2 mm and to within 0.000 2 mm for d < 0.2 mm.

The scale of the measuring microscope shall be verified by measurements made on a stage micrometer or any other suitable measuring device at a minimum of five intervals over each working range. The difference between readings corresponding to any two graduation lines of the measuring microscope shall be correct to within ± 0.1 % of d for d > 0.5 mm and to within ± 0.000 5 mm for d < 0.5 mm.

These requirements are plotted in Fig. 56. The requirements given in OIML International Recommendation No. 10 [SR-27] are the same for the lower ranges, but these values are maintained constant (0.5 and 0.2 µm, respectively) over the whole range of measured diagonals.

It should be mentioned, for the sake of comparison, that the corresponding values specified in ISO 146-1984 [SR-13] for commercial Vickers testers are in general five times higher than those given in ISO 640, but for the small indentations (20 to 50 µm) a maximum error of 0.5 µm is specified. This value is considered, at present, as the limit of technical possibilities, thus both standardizing and industrial testing laboratories should approach this limit as closely as possible.

To avoid misunderstanding it must, however, be remarked that the 0.5 µm accuracy limit regards checkings by stage micrometers only, not the measurement of the indentation proper. Consequently an evaluation of the uncertainty of Vickers measurements based on this uncertainty value, usually underestimates actual values [B-13].

OIML RI No. 10 formulates a requirement concerning the optical system: "The microscope intended to measure the indentations must be adjusted in such a way as to produce uniform illumination of the entire field of vision, as well as maximum contrast between the indentation and the tested surface".

This last mentioned requirement is an expression of the necessity of taking care to prevent errors of the kind ba) (instrumental, random). All the other requirements quoted above concern the instrumental systematic errors (kind aa).

The prescriptions on the correct illumination given by the ASTM in [SR-54] were quoted already in chapter 3.2.1.

ASMW-VM 145 [SR-51] gives more details on the test method. The selected interval should be checked on the stage micrometer ten times in a series. The interval should be about 25 % of the measuring range of the given scale. Checking should be carried out with all the possible magnification ratios. This checking should be carried out only on new instruments or after changes or repair operations.

The Japanese Standard [SR-52] specifies ± 0.2 % for the permitted magnification error and ± 0.2 µm for the bias of the zero point.

5.3. Instrumental errors

The greatest part of the uncertainty of Vickers and Brinell hardness values is due to indentation measurement. Actual uncertainties are often higher than what could be expected from the specifications given in Standards for hardness testing.

Systematic and random errors of the measuring instrument [aa) and ba)] often cannot be separated. Some experimental methods and results give an idea on the character and magnitude of these errors.

RATIU and PREXL [R-7] examined a measuring microscope with 10 different objective-ocular lens combinations, and bright field illumination. Indentation diagonals in the range of 150-600 µm were measured with numerical apartures from 0.06 to 0.65 (total magnification from 42x to 600x). At higher numerical apartures diagonals were measured systematically 3-4 µm longer. Standard deviation of diagonal measurement was reduced from (1.5-4)µm to (0.3-0.6)µm if aperture and magnification increased in the above mentioned range. The lower values in each bracket apply for Vickers diagonals parallel with the direction of surface machining of the block or being at 45° to that direction, while the higher values apply for diagonals perpendicular to machining direction. In the latter case the corners of the indentation are not well defined.

MEYER and ROSSOW [M-14] made further examinations on the effect of numerical aperture with three commercial measuring microscopes. No significant effect was observed. In some partial measuring series an effect similar to that observed in [R-7] was found, nevertheless both positive and negative changes occured. Consequently no significant influence of the numerical aperture and magnification on the measured value can be stated for the three examined microscopes.

Significant differences were found, however, between values determined on four microscopes on the one hand, and two projectors on the other hand. 18 indentations in the range 80-640 µm were measured. The microscopes gave always higher diagonal length values, the difference being :

around 2 μm in the range 80-160 μm and nearly constant 4 μm in the range 320-640 μm.

The effect of numerical aperture was studied also by THIBAULT and NYQUIST (quoted in [B-13]). The differences in the measured value of the Vickers indentation diagonal, in fuction of numerical aperture is shown in Fig. 57. The origin of this effect was not clearly explained.

Other errors caused by the measuring microscope were described by ILLIG [I-3]. An optical distortion of the objective may result in different magnification ratios in different areas within the visual field. This effect is less than 1 ‰ in the case of good instruments. Another error source is the micrometer indicating the displacement of the graticule. This error can be of the order of $\pm 2/N_{ob}$ μm, where N_{ob} denotes the magnification of the objective. A third error source is the adjustment of magnification to the measuring graticule arranged in the image plane. In the case of good microscopes this error does not exceed $\pm 2/N_{ob}$ μm. By a good adjustment this value can be reduced to $\pm 0.5/N_{ob}$ μm.

The systematic differences of the measurement of the same indentation in two laboratories by BARBATO and PETIK [B-11] are shown in Fig. 58. These values include both instrumental and personal error sources.

5.4. Personal systematic errors

To clarify the relationship between the visual judgment of a person who operates a measuring apparatus and the accuracy of measurement, YANO [Y-19] made extensive research work on the interrelation between the operator and measuring apparatus. The problem has been taken up as a project of the man-machine system. The measurement of Vickers indentations is a typical example in which personal difference in visual judgment occurs. To find personal differences, an experiment was made with variance analysis according to the following factors : Personal differences, skill level of persons, repetition uncertainty, interactions between these factors.

The experiment has shown that differences between different persons are caused by many different factors which are intermingled with each other. Thus it is not always easy to recognize the personal differences adequately or to prove that personal differences are not included in the measured value. It cannot be said that a person with high measuring ability is always free from measurement bias. According to their long time behavious, microscope operators can be classified into

stable type,
improving type, and
unstable type.

Personal differences are influenced by he degree of experience in measurement. But the trend was studied in [Y-19] also from the aspect of the personality of each person. It has been observed that psychological reactions, including the speech and behaviour of the persons performing measurement work, contain some factors which are inherent in that person, and these inherent factors seem to have something to do with the accuracy of measurement. Therefore measuring persons were given a personality test (Moseley's Personal Test). The tests have shown that emotionally stable and introversive personalities are better suited for measurement work and for technical professions in general. Emotionally unstable, extroversive and agressive personalities seem to be suited for administrative and managerial professions. In summarizing the results of YANO's experiments it was stated that in visual judgment accuracy of measurement varies according to various factors including the experience, practice, training and personality of a man as the sensor. Physical stimuli might also affect in one way or another the mental response of the measurer but the impacts of such stimuli are not so great as to affect the result of measurement.

The results of several experiments were published which show the degree of possible personal differences in Vickers indentation diagonal measurement. The results of one of these experiments will be discussed in detail while the results of several other summarized in a comparative diagram.

PETIK, ČUTKA et al. [P-4, C-8] published the results of an experiment in which five persons coming from five national standard laboratories performed comparative measurements in the same laboratory, on the same measuring microscopes, and during a short period of time . Indentations of approx. 50, 100, and 150 µm diagonal length (five of each) were prepared on a block. Each person measured them on three different microscopes on the same day. These measurements were repeated on the two following days. Systematic differences between persons are shown in Figures 59, 60 and 61. The horizontal axis was taken as the mean of the values measured by persons marked 1 to 5. (The values measured by the person marked 6, who was the second person from the laboratory where the comparison were made, were not taken into consideration at the evaluation). With a few exceptions, results were within ± 0.4 % (i.e. difference of 0.8 % between two persons at the maximum). The personal "deviation" of observer 5 from all the others is apparent in Fig. 60 and 61. It should still be taken into consideration that four persons participating in this experiment were working as guests in this laboratory on microscopes they were not accustomed to.

The main characteristics of the three microscopes used in this experiment are the following :

Magnification	Objective Magnification	Objective Numerical aperture
400 x	40 x	0.70
200 x	20 x	0.35
100 x	10 x	0.18

Results of similar experiments to determine systematic differences of persons having more or less practice in indentation measurement, or the daily variations of the same person, are summarized in Fig. 62.

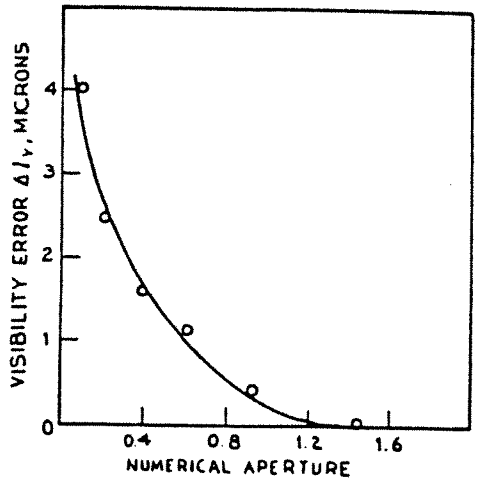


Fig. 57. Differences in Vickers indentation measurements, using different numerical apertures

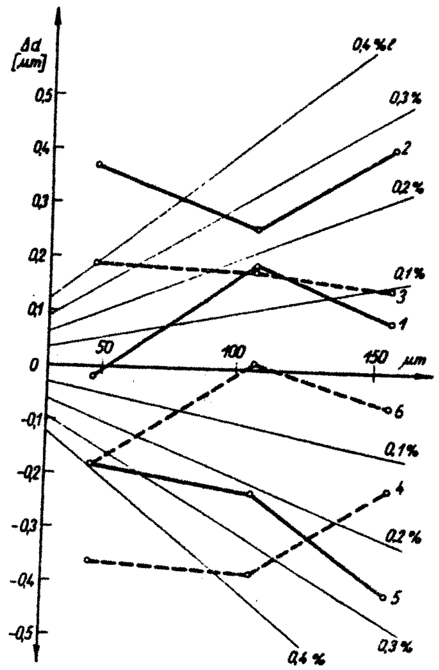


Fig. 59. Personal differences at measuring Vickers indentations at 400 x magnification

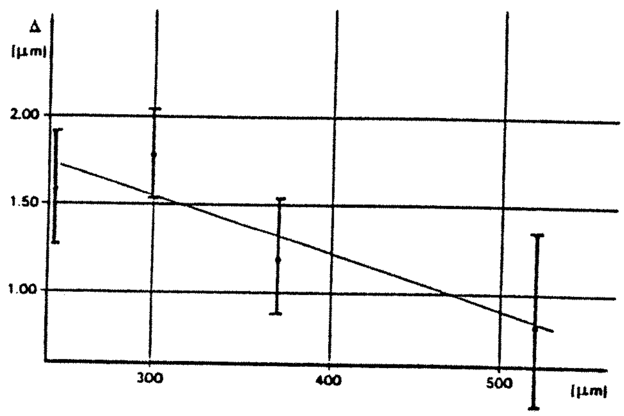


Fig. 58. Differences of the determination of the same indentations in two laboratories

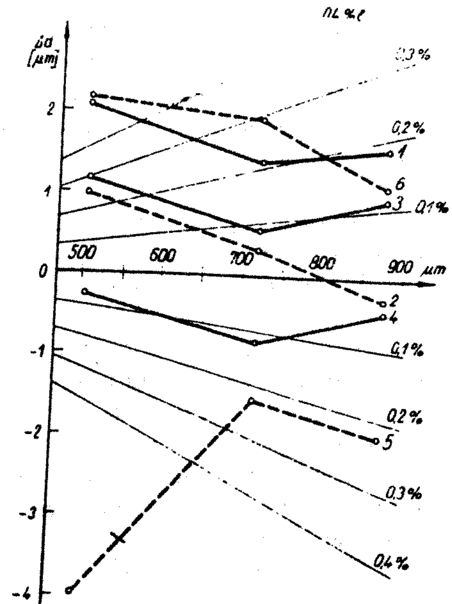


Fig. 61. Personal differences at measuring Vickers indentations at 100 x magnification

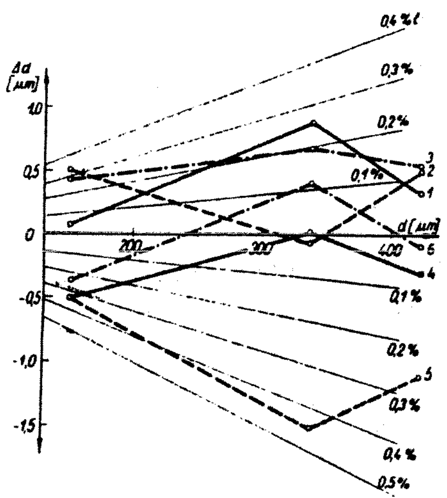


Fig. 60. Personal differences at measuring Vickers indentations at 200 x magnification

Two examples illustrate how to use this diagram :

(a) Diagonals of about 10 to 50 µm length were measured by 4 persons. The difference between the maximum and minimum determinations was approx. 0.7 µm [H-11].

(g) The same person measured a diagonal of about 80 µm length repeatedly during 10 days. The difference between the maximum and minimum determinations was approx. 1.2 µm [P-3].

In [W-18] and [B-10] personal differences, in the case of perfect indentations, are indicated as being of the order of 0.5 µm. According to [C-8] diagonal length d can be determined within ± 0.1 % d in the standardizing laboratory.

The separate evaluation of diagonals measured in vertical or horizontal position in the field of vision [P-3, Y-19] revealed that some observers have a certain preference for one direction. Human eyes function differently depending on whether they observe an image vertically or horizontally.

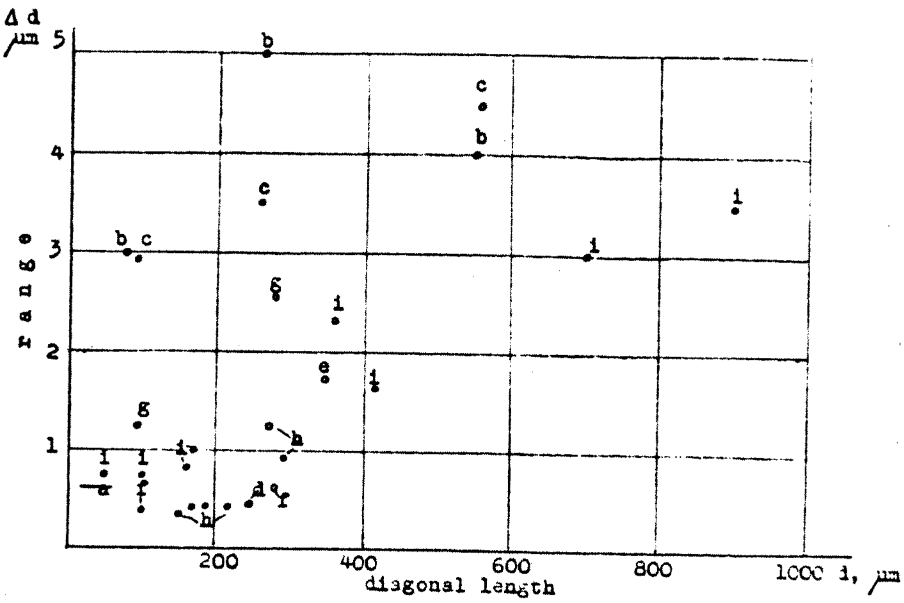
To establish long-time variations of personal bias WOOD and MARRINER [W-18] organized an experiment extending over two and a half years. Two sets of 10 indentations (approx. 100 and 250 µm) were read intermittently by four observers. Over the test period three observers have maintained their level of reading to ± 0.2 µm and the general level was unaffected by cleaning and realignment of the microscope at the middle of the experiment. The fourth observer was initially completely inexperienced in microscope work and he gradually adjusted his setting criterion until it approached the general level, although, at the end of the experiment, he was not yet as consistent as the more experienced observers.

These experiments show that the weakest point of Vickers hardness measurements is the diagonal determination. Though repeatability of measurements, as we shall see in the next chapter, is often better than the optical resolution of the microscope, the setting of the graticule to the corners of the indentation is burdened with relatively high personal bias. Limits of accuracy are certainly not imputable only to the limitations of optics [B-10]. A portion of the uncertainty is actually due to the measurand itself. The vertex of the indentation is not well defined, the operator makes a psychological extrapolation of the indentation sides at a point that only he himself characterizes as the vertex. This subjective process makes identical measurements by different operators nearly impossible.

5.5. Correction for systematic personal differences

As the personal bias at measuring Vickers indentations may change with time, it is desirable to have a reference standard available, namely an indentation the conventional true value of which is known. Various solutions are in use or were proposed.

5.5.1. The set of calibrated indentations (Fig. 63) can be conveniently prepared on an old gauge block not suitable any more as a length standard [C-2, C-8]. The indentations are measured by several persons,



a	H-11	4 persons
b	H-11	6 persons
c	K-7	6 persons
d	M-2	2 persons
e	S-12	several persons
f	P-3	4 persons, means of values measured on 10 days
g	P-3	Differences measured by the same person during 10 days
h	R-12	The same person during 7 days
i	P-4	5 persons, means of values measured on 3 days

Fig. 62. The range of Vickers indentation diagonal values as determined by different persons. Data published in the indicated references

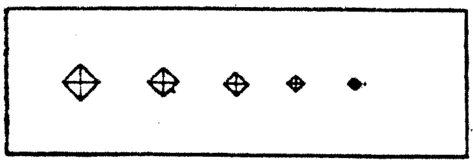


Fig. 63. Set of calibrated Vickers indentations

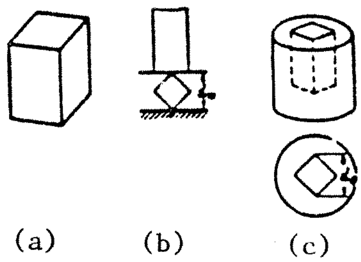


Fig. 65. Calibrated imitation of a Vickers indentation

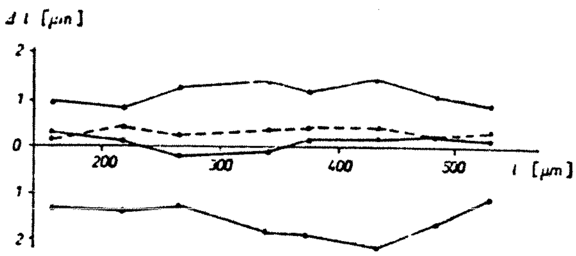


Fig. 64. Personal corrections of four members of the staff of a laboratory

on different microscopes, or in different laboratories. From these measured values the "conventional true value" of the diagonal length will be established by a suitable weighting procedure.

The procedure of determining the conventional true value or standard value of the set of calibrated indentations is described in all details in the Japanese Standard JIS B 7735-1981 [SR-52]. The confidence limit with 95 % confidence coefficient is given as ± 0.6 µm (when using an objective lens of 10 to 15 times magnification), or ± 0.4 µm (for more than 20 times magnification). According to ČUTKA the true value can be defined better than 3 s = ± 0.2 % d [C-6].

According to measurements of HIDA [H-17] the personal correction is practically independent of diagonal length.

The use of calibrated indentations in measurement practice is the following :

Sets of calibrated indentations with certificates of the true value should be given to all persons engaged in Vickers measurements, or should be available with all measuring microscopes. At evaluating Vickers indentations, the measuring person measures both these and a calibrated indentation. The difference between the stated value and the measured value is taken as correction to the measured value of the unknown indentation.

ČUTKA [C-2, C-8] published the comparison of the personal correction values of four persons working in the same laboratory (Fig. 64). The two external curves which represent personal corrections of the order of 1-2 µm are the result of setting errors shown in Fig. 43, under a) and b). When considering personal corrections, confidence limits should be taken into consideration [H-2, H-16].

If the standard deviation of an observer within a day at n measurements is designated by σ_{ω}, and his day to day variance during r days is σ_R^2, then the uncertainty of the observer is :

$$\sigma_{\omega}' = \sqrt{\frac{\sigma_{\omega}^2}{n} + \sigma_R^2}$$

Accordingly the relative bias of the mean values $\bar{x}_a$ and $\bar{x}_b$ determined by two observers a and b, taking into consideration the uncertainties too, is found to be :

$$(\bar{x}_a - \bar{x}_b) \pm \sqrt{\frac{\dfrac{\sigma_{\omega a}^2}{n_a} + \sigma_{Ra}^2}{r_a} + \frac{\dfrac{\sigma_{\omega b}^2}{n_b} + \sigma_{Rb}^2}{r_b}}$$

Employing these formulae, some experimental values were published by HIDA [H-2, H-17] (n = 10, r = 5) :

Observer	bias from total mean (µm)	$\sigma_{\leftrightarrow}$ (µm)	σ_R (µm)	$\sigma_{\leftrightarrow}'$ (µm)	
A_1	+ 0.86	0.57		0.57	skillful researchers of Vickers hardness
A_2	+ 2.04	0.53	0.15	0.55	
A_4	- 0.66	0.39	0.19	0.43	
A_3	+ 0.28	0.79		0.79	
A_5	- 0.90	0.80	0.07	0.80	experts of fine measurement
A_6	- 1.53	0.58	0.31	0.66	

Day to day variance was very small in each case. Uncertainties are relatively high in comparison with bias values, what is characteristic for measurements performed in other laboratories too.

Automatic measuring instruments are employed more and more, but these too have to be calibrated manually in many cases. Accordingly the necessity of standard Vickers indentations remains also in the future.

5.5.2. Another solution of calibrated indentations was proposed by MEYER [M-11] (Fig. 65). A metal bar of square cross section is cut to a convenient length (a) and its diagonal length measured by a length measuring instrument (b). Herafter the bar is embedded in a suitable plastic material, to have an imitation of a Vickers indentation with known diagonal length. Color of the square bar and of the plastic material should possibly imitate colour and surface finish conditions of actual indentations. Nevertheless this imitation differs from actual conditions as it has no "indentation", the measured square surface is plane. The production of such imitations is practicable only for the higher range of diagonal lengths.

5.5.3. To determine personal corrections for diagonal measurements MEYER [M-12] proposed a very simple method. At checking the correctness of a commercial Vickers hardness tester by the help of a standardized test block, not only the indentations made by the tester, but also the indentations which had been made at the standardization of the block should be measured by the microscope. In this way a personal correction can be employed similarly as in point 5.5.1. To realize this method the identations made for the standardization of the block have to be identified and the value of their diagonal length stated in a certificate.

5.5.4. For microhardness measurements HIDA and YAMAMOTO [H-11, H-17] elaborated a statistical method for the determination of the absolute value of diagonal length. The experiment necessitated 900 Vickers indentations made with ten different test forces which form a geometrical series. The diagonal length values were measured by four expert observers. The regression analysis permitted to determine the "absolute value" of indentations within ± 0.1 µm.

Questions of employing more elaborate correction values are discussed by ROSSOW [R-12]

5.6. Personal random errors

Several authors published the standard deviation values of repeated measurement of Vickers indentation diagonals. These values are shown, in function of diagonal length, in Fig. 66. The values of the five persons participating in the experiment described in [P-4] were in the range delimited by the dotted lines. (The systematic differences found in this experiment are given in Fig. 59-61). Further standard deviation values were published without indicating the diagonal length. These are :

0.1 µm	in [B-10], [W-18], [M-12]
0.1 - 0.3 µm	in [K-7]
0.2 - 0.4 µm	in [H-2]
0.3 µm	in [M-14]
0.3 - 0.5 µm	in [B-2]

Claimed uncertainty values for diagonal length measurement can be found also in [P-17] (Hardness Standard Machines of National Institutes of Metrology). Some institutes specified their values in function of diagonal length (Fig. 67), while others independently of the diagonal. These are indicated at the right side of Fig. 67, each dot representing one reported microscope used for standardization work.

5.7. How to use published uncertainty values ?

The previously mentioned values on the uncertainty of Vickers microscopes should be used only as examples. Based on these values, hardness standardizing laboratories can check their own microscopes, can employ corrections if necessary. This may help to estimate measuring capabilities objectively.

6. Uncertainty of Brinell indentation diameter measurement

The main difference, in comparison with Vickers indentation measurements, is that Brinell indentations are larger, consequently magnification ratios are not so high. Different kinds of illumination may have an influence as described earlier, on account of ridging or sinking at the circumference of the Brinell indentations.

6.1. Specified requirements

OIML International Recommendation No. 9 [SR-28] and International Standard ISO 726-1982 [SR-18] specify the following requirements for a measuring microscope to be used for the standardization of Brinell hardness test blocks :

The scale of the measuring microscope shall be graduated to read to 0.002 mm for indentations made with 10 and 5 mm balls and 0.001 mm for indentations made with balls of less than 5 mm diameter.

The scale of the measuring microscope shall be verified by measurements made on a stage micrometer at a minimum of five intervals

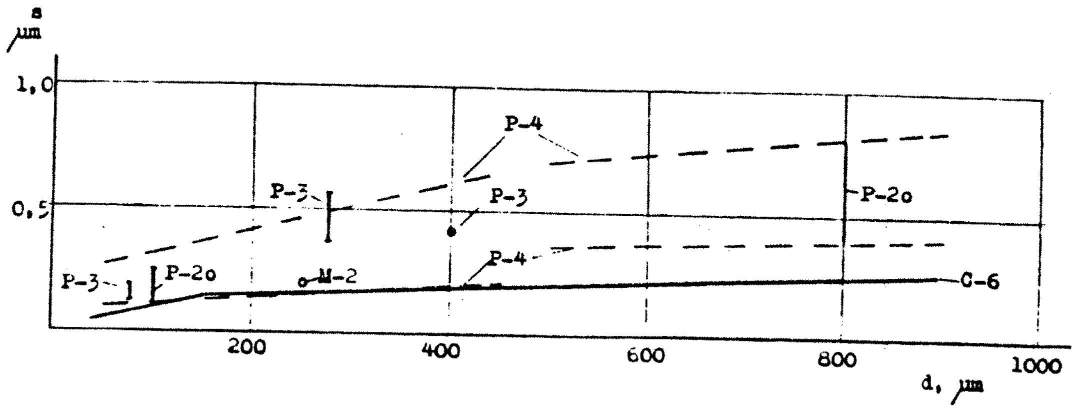


Fig. 66. Standard deviation values of repeated Vickers indentation measurements. Values published in the indicated references

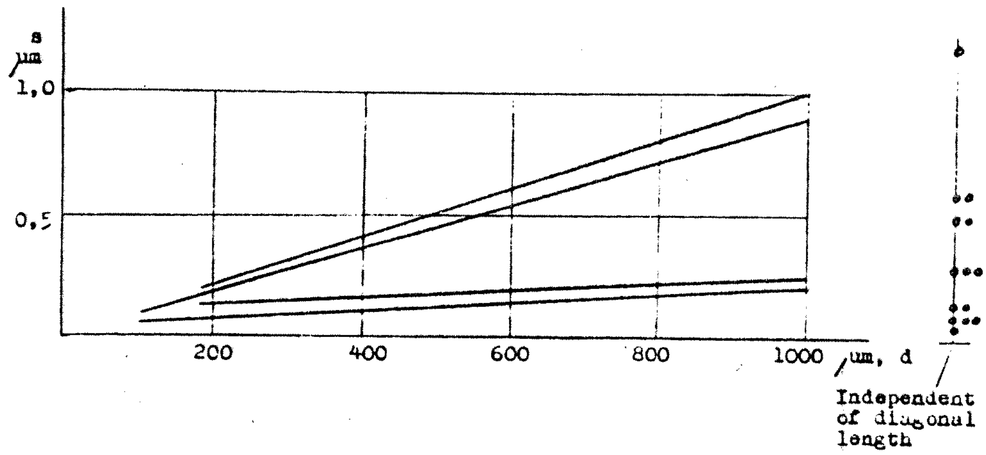


Fig. 67. Stated uncertainty of different Vickers measuring microscopes [P-17]

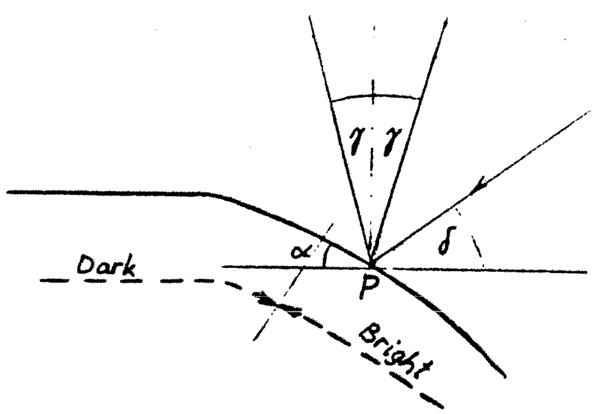


Fig. 68. Profile of the border of a Brinell indentation with oblique illumination

over each working range. The difference between readings corresponding to any two graduation lines of the measuring microscope shall be correct

- within ± 0.002 mm for 5 and 10 mm diameter balls
- within ± 0.001 mm for smaller balls.

6.2. Instrumental errors

RATIU and PREXL [R-7] examined the measured values of Brinell indentations having a diameter of 1 to 2 mm. Tests were made on a measuring microscope both with bright and dark field illumination. In the latter case light beams had an included angle of 45° with the surface of the specimen. A projector apparatus was also used in which the oblique illumination light beams arrived at a much higher angle. The first result was that the contrast of the indentation in bright field illumination was much worse than with oblique illumination.

The standard deviation for repeated measurements was ± 2.7 µm for the vertical illumination (bright field) and ± 1.5 µm for oblique illumination (dark field). With bright field illumination no significant influence of the mumerical aperture on the measured diameter was found. In dark field (oblique) illumination, however, diameters were systematically found about 2 µm larger, when the numerical aperture was increased from 0.06 to 0.30 (at total magnifications of 21 x to 84 x). This phenomenon can be understood by observing Fig. 68, where the scheme of the border portion of a Brinell indentation is shown. At point P the surface has an included angle α with the horizontal. Illumination arrives at an angle δ. The point is observed by the objective having a half angle of opening of γ (numerical aperture = sin γ). It can be shown by geometrical calculation that the border between dark and bright sections is at :

$$\alpha = 45° - \frac{\delta}{2} - \frac{\gamma}{2}$$

This shows that with higher numerical aperture (higher γ) α becomes lower, that is the more "flat" sections of the indentation are also included, the measured value is higher. The formula gives the reason for the fact that values measured with the projector [R-7] were systematically higher : δ was much higher than the 45° used on the microscope.

The same examination for bright field illumination was carried out by BARBATO [B-13]. In this case the effect of changing the numerical aperture is contraty to that observed with dark field illumination. In Fig. 69 three points on the border of the indentation are shown, characterized by the inclination angles α_1, α_2, and α_3 of the deformed surface. For the sake of simplicity it was assumed that tha angle of the lens aperture and the angle of illumination are equal, designated by γ. At point P_3 the cone of illumination is vertical, the reflected cone of light is inclined with respect to the former by an angle of 2 α_3. Since there is no overlapping of the two cones, no reflected light reaches the objective, point P_3 is observed as being dark. At point P_1 the cones of incident and reflected light are partially overlapping, consequently this point is observed in the microscope as bright. The border between the bright and dark section is at point P_2 where the two cones are in

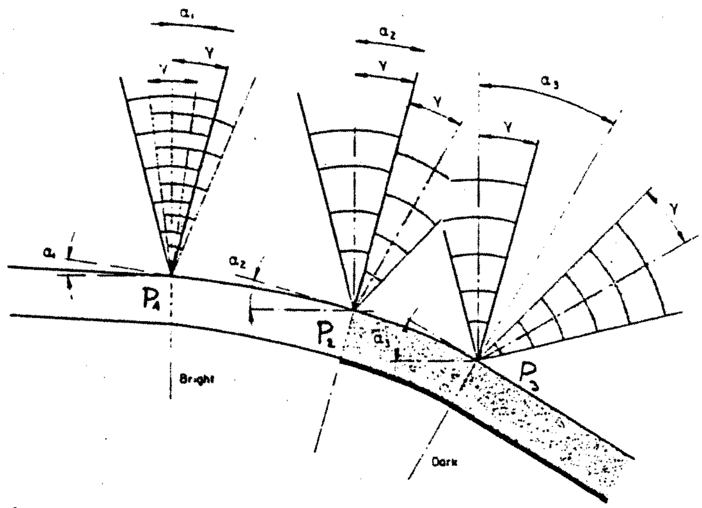


Fig. 69. Brinell indentation in bright field indentation

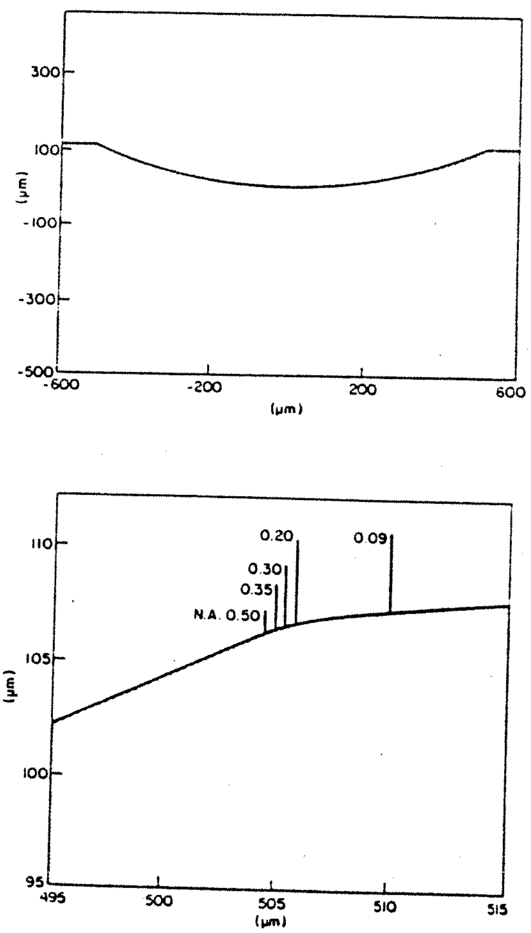


Fig. 70. Profile of a Brinell indentation and indentation radii measured with different numerical apertures
(Hardness level approx. 200 HB 2,5/187,5)

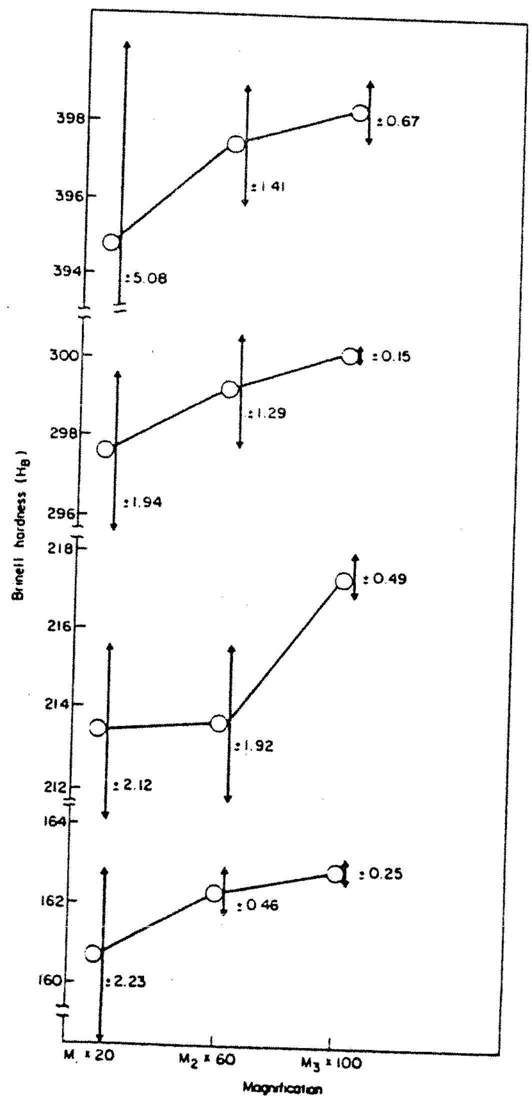


Fig. 71. Effect of microscope magnification on measured HB value. Systematic and random errors

contact. Accordingly the dark section (the observed indentation) is characterized by

$$\alpha \geq \gamma$$

This means that higher numerical aperture results in smaller indentation, the "flat" portions at the border are not included. Fig. 70 shows the profile of a Brinell indentation [B-13]. The lower portion of the figure shows the radii (not diameter !) of the indentation determined with different numerical apertures. In the experiment the consequences of altering the focal plane were also examined, but this effect was found to be much less than that of the numerical aperture. In consequence of the displacement of the focal plane by 40 mm from normal position, measured indentation radii changed only by about 0.5 µm. The effect of altering numerical aperture can be summarized as follows :

If numerical aperture increases,

with dark field illumination	measured diameter increases,
with bright field illumination	measured diameter decreases.

The experimental results published by MAYER [M-13] and OETTEL (O-1) confirm this statement.

The effect of magnification of the measuring microscope on measured Brinell hardness values as determined by SHIN et al. [S-11] is shown in Fig. 71. Both systematic differences and random uncertainty are indicated. It is apparent from this diagram that the changing of magnification from 20 x to 100 x caused a systematic error of 2 to 3 HB; diagonals were measured at 20 x magnification approx. 20 to 30 µm larger than at 100 x (the difference is of the order of 0.5 %). But the uncertainty of measurement at the magnification of 20 x is of the same order as the systematic error. Uncertainty was considerably reduced at higher magnifications.

6.3. Personal systematic errors

The range of Brinell indentation diagonal values measured by five persons in the experiment described in [P-4 and C-8], at magnification ratios of 50 x and 25 x, on different indentations are shown in Fig. 72. The differences between values of other five persons, working with a newly developed microscope described by KERSTEN [K-10] are indicated by the oblique lines shown in the same figure. Ranges were different in function of ball diameter.

Calibrated sets of indentations are used for determining personal bias at Brinell measurements too. The true value of these calibrated indentations can be defined according to CUTKA [C-5] with an uncertainty of :

$$3s = \pm\ (1.1 + 0.00034\ d),$$

all values being substituted in µm.

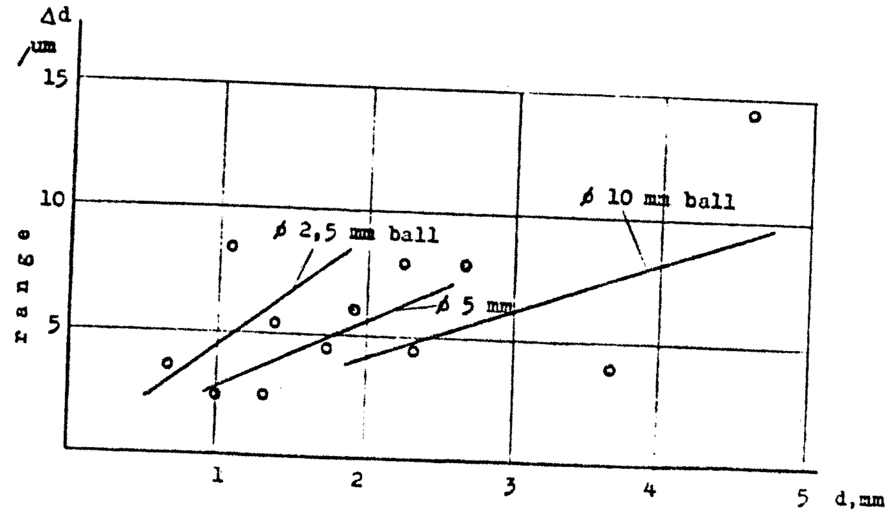


Fig. 72. Range of Brinell indentation diameter values obtained by different persons.
Data published in the following references
P-4 5 persons, 50x and 25 x
K-10 5 persons, 100x

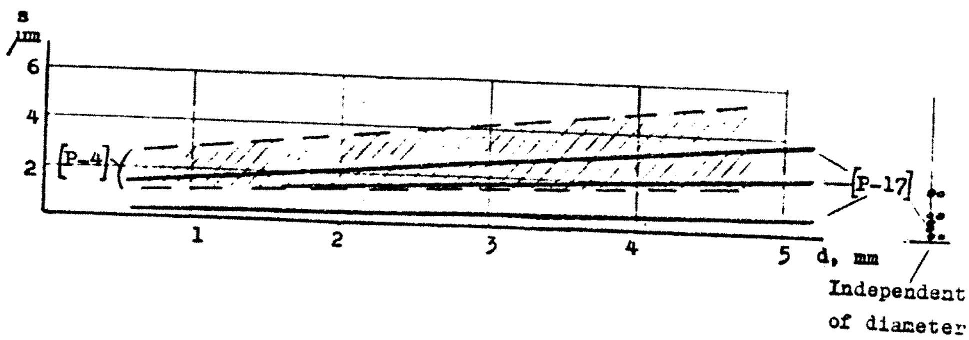


Fig. 73. Standard deviation values of repeated measurements of Brinell indentation diagonals in an experiment [P-4] and stated values P-17

6.4. Personal random errors

The standard deviation values of the five persons participating in the experiment described in [P-4] were within the field delimited by the dotted lines in Fig. 73. The standard deviation values for measuring Brinell indentations of Ø 3 to Ø 5 given in [S-11], depending on magnification, were the following :

Magnification	s, μm
20 x	17...31
60 x	5...20
100 x	3... 6

The standard deviation of 10 measurements of the some identation (in two directions) is stated as 0.36 x 10^{-3} in [B-15].

7. Uncertainty of the complete hardness standard equipment

The basic problems of measurement uncertainty are much discussed in our days. Even generally employed basic concepts are reformulated. The classification according to systematic and random uncertainties is often not satisfactory. Experience has shown that it is difficult to find methods equally suitable for each field of measurement. International Organizations published independent documents on the statement of uncertainties in different fields, such as e.g. ISO for flow measurement (ISO 5168-1978) and for reference materials (ISO Guide 35-1984). The International Committee for Weights and Measures (CIPM) recommended the experimental use of a document on the statement of uncertainties arrived at by different methods, so as to ensure a certain uniformity in metrological practice.

Also in the field of hardness measurement different methods for the determination and statement of uncertainties were published. It is not envisaged to describe here all the details of these methods. The general state is indicated, problems and difficulties discussed, so as to help to avoid erroneous conclusions [P-24].

The components of the overall uncertainty of a hardness standardizing machine are the following :

- Repeatability. ISO 3534-1977 [SR-19] gives the following definition :

  2.85 repeatability :

  a) Qualitatively

  The closeness of agreement between successive results obtained with the same method on identical test material, under the same conditions (same operator, same apparatus, same laboratory and short intervals of time).

  NOTE - The representative parameters of the dispersion of the population which may be associated to the results, are qualified by the term "repeatibility".

Example : Standard deviation of repeatability, variance of repeatability ...

b) Quantitatively

The value below which the absolute difference between two single test results obtained in the above conditions may be expected to lie with a specified probability.

In simple words : This is the short time random variability of the equipment.

- Reproducibility. ISO 3534-1977 :

2.86 reproducibility :

a) Qualitatively

The closeness of agreement between individual results obtained with the same method on identical test material but under different conditions (different operators, different apparatus, different laboratories and/or different times).

NOTE - The representative parameters of the dispersion of the population which may be associated to the results are qualified by the term "reproducibility".

Example : Standard deviation of reproducibility, variance of reproducibility ...

b) Quantitatively

The value below which the absolute difference between two single test results on indentical material obtained by operators in different laboratories, using the standardized test method, may be expected to lie with specified probability.

In the case of a given hardness standard equipment, "under different conditions" means different operators of the same laboratory and different times, i.e. the long time random variability.

- Unknown systematic deviation from the conventional true value, for which the International vocabulary of basic and general terms of metrology [SR-20] gives the following definition :

1.19 Conventional true value (of a quantity)

A value of a quantity which, for a given purpose, may be substituted for the true value.

NOTE - A conventional true value is, in general, regarded as sufficiently close to the true value for the difference to be insignificant for the given purpose.

Example: Within an organization, the value assigned to a reference standard may be taken as the conventional true value of the quantity realized by the standard.

The unknown systematic deviation from the conventional true value to be realized by the hardness standard can be specified by an estimation in the form of a standard deviation. This means that it belongs to the random uncertainties.

- Systematic deviation from the (conventional true) value maintained by a higher order standard (if it exists in a traceability scheme). This is a systematic error, its value is again burdened by a random uncertainty.

Research work in connection with this problem was directed in mist cases at some of the above components. The experimental method used by different workers was different, this makes the comparison of values often difficult.

Published values may be incomplete. The meaning of the well known terms "accuracy", "precision", "uncertainty" may be different (even in standards or official prescriptions of different countries). Some sources regard the standard deviation as "uncertainty", while others give 2 or 3 standard deviations as a measure of uncertainty or precision, or call the three standard deviation a "limit error". It is not always clear in published data whether the standard deviation refers to a single measurement, or to the mean of several measurements. And in the latter case, of how many measurements ? When stating the uncertainty of a hardness standardizing machine, some other factors (ununiformity of the blocks, long time variations, unknown systematic errors etc.) may also be included in the published value. Therefore great attention is required to judge correctly the content of published uncertainty values. In the followings the methods and results of different researchers are described. (The order of description mostly follows the order of publication).

7.1 Repeatability

From the conditions given in the definition cited above, "identical test material" cannot be fully ensured, since hardness testing destroys a small spot on the specimen, the measurement cannot be repeated at the same place. Even the surface of the best specimens, of standardized test blocks, is not completely of identical hardness as it was discussed in details in the OIML-Publication "Hardness test blocks and indenters" [P-22]. Consequently the variation of the results of repeated measurements made by a hardness standardizing machine is due partly to the repeatability of the machine and partly to the ununiformity of hardness of the block. The two factors should be separated by appropriate methods.

Suitably planned experiments and the statistical method of variance analysis permit a separation of block and machine effects.

YAMAMOTO, YANO, YAJIMA [Y-4] employed the split plot experimental method to separate the factors time, indenter, block surface, machine, various interactions. The residual variance of the analysis is characteristic of the repeatability of the standardizing machine itself, for which values of 0.10 - 0.12 HRC were obtained.

SMOLITCH [S-7] found repeatability values of ± 0.08 HRC, after the separation of the factor of ununiformity of the block surface.

MARRINER [M-1, M-5] employed the experimental method of Graeco-Latin squares to separate the factors indenter, block surface along two co-ordinates and the order of measurements. With this method each indentation is to be made at a predetermined point. The residual variance characterizing the standardizing machine was found to be ± 0.12 HRC at 64 HRC. PETIK [P-7, P-11, P-12] employed the method of Latin squares for the evaluation of several hundred blocks. The regression line calculated from the residual variance values obtained at different hardness levels is shown in Fig. 74. The line denoted by σ can be given analytically as :

$$\sigma = 0.003\ (100 - H) \qquad [\mathrm{HRC}]$$

where H denotes the hardness level in HRC.

The line s_{1x} in Fig. 74 shows the repeatability of measurements, before the separation of the variance due to the ununiformity of block hardness.

The residual variance values obtained on Vickers blocks (test load 294.3 N) are shown in Fig. 75. According to the variance analysis of Latin squares with Vickers indentations the variability due to surface ununiformity was significant only in a few cases with respect to the residual variance (repeatability of the machine). Consequently the surface factor is included in σ. In Fig. 75, for purposes of comparison, also the σ values given in Fig. 74 were converted into HV values. This is denoted by σ(HRC). Though it is somewhat lower than σ(HV) (probably due to the uncertainties of the microscope), the difference is not great. It should be noted that the values given in Fig. 74 and 75 represent the standard deviation of a single measurement.

By comparing Fig. 74 and 75 one may ask why the slope of σ is different. Rising with increasing HV-hardness and decreasing with increasing HRC-hardness. This is only an apparent contradiction, caused by the non-linear correlation between the two hardness scales, shown on Fig. 76. The lower curve in this figure shows, how many HRC units correspond to a difference of 10 HV at different hardness levels : About 2 HRC/10 HV at low hardness and less than 0.5 HRC/10 HV at high hardness levels. This indicates that the Vickers scale is more extended at higher hardness values than the Rockwell C scale. If the σ values for both the Rockwell and the Vickers machine are represented on the same scale (as in Fig. 76) the character of the curves, the direction of slope is similar.

Repeatability values published by ČUTKA [C-1, C-7, C-9] can be taken from the scheme presented in Table 5. The components corresponding to data discussed in this chapter are the

- random uncertainty of test force application (δ_5),

- reproduction of the group standard of indenters (δ_6),
- uncertainty of depth measurement (δ_7).

The values stated are error limits δ, being equal to 3s. The quadratic addition of the three components enumerated above,

$$\delta_0^2 = \delta_5^2 + \delta_6^2 + \delta_7^2$$

gives the following values :

δ_0 = 3s = 0.10 HRC (with spiral microscope)
= 0.04 HRC (with laser interferometer)
= 0.10 HRN (- " -)
= 0.05 HRT (- " -)
= (0.1 - 0.25)% HV (estimation)
= (0.2 - 0.35)% HB (in case of Ø 10 or Ø 5 balls, estimation)
= (0.25 - 0.45)% HB (in case of Ø 2.5 balls, estimation).

7.2. Reproducibility in a long time interval

By definition, reproducibility differs from repeatability in the conditions of tests. When speaking of the reproducibility of a hardness standardizing machine, the long time effect is preponderant and the operator may also be different. But the apparatus and the laboratory is of course the same.

In the OIML-Publication "Hardness test blocks and indenters" [P-22] the questions of stability of hardness in time were discussed in detail in chapter 5. Experiments to establish long time variability were described there in point 5.3. It was stated that it is impossible to separate experimentally the variations in time of the block and of the machine, respectively. The opinion of most researchers, based on experience is that most of the observed variation is due to the block. YAMAMOTO [Y-4] published a control chart of a HRC machine. At 67 HRC the control limits were ± 0.16 HRC. PETIK [P-24] estimates that the uncertainty due to long-time variations of the standardizing machine can be taken as equal to the repeatibility of the machine. MARRINER [M-7] estimates that standardizing machines have remained stable well within ± 0.5 % HV 30 for more than 10 years. CUTKA [C-1] estimates that long-time variations of the standardizing machine may cause maximum errors not exceeding the following values.

δ_8 = 3s = ± 0.16 HRC (with spiral microscope)
= ± 0.12 HRC (with laser interferometer)
= ± 0.15 HRN (- " -)
= ± 0.15 HRT (- " -)
= ± (0.1 - 0.15)% HV
= ± (0.1 - 0.15)% HB

The Japanese Standard Specification [SR-53] specifies the following permissible values for the control limits for the mean values of three measurements. (Points of the control charts should be plotted approximately once a week).

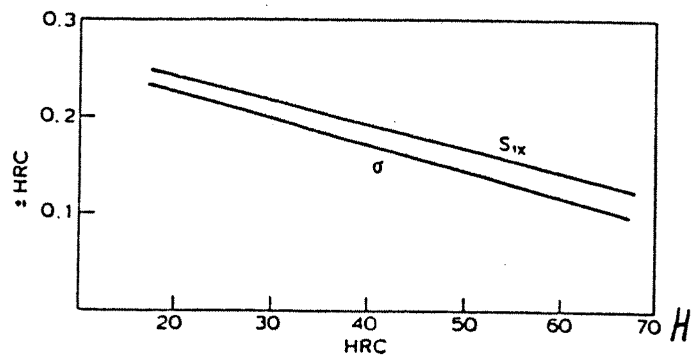


Fig. 74. Repeatability of a Rockwell C standard hardness measuring equipment (with and without the uncertainty of the standardized block)

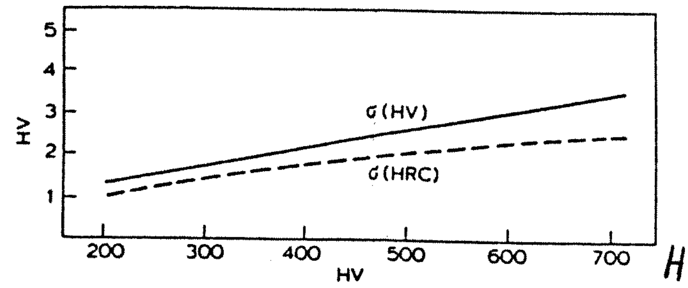


Fig. 75. Repeatability of a Vickers standard hardness measuring equipment (Similar values of the Rockwell equipment, converted into HV units, plotted by broken line)

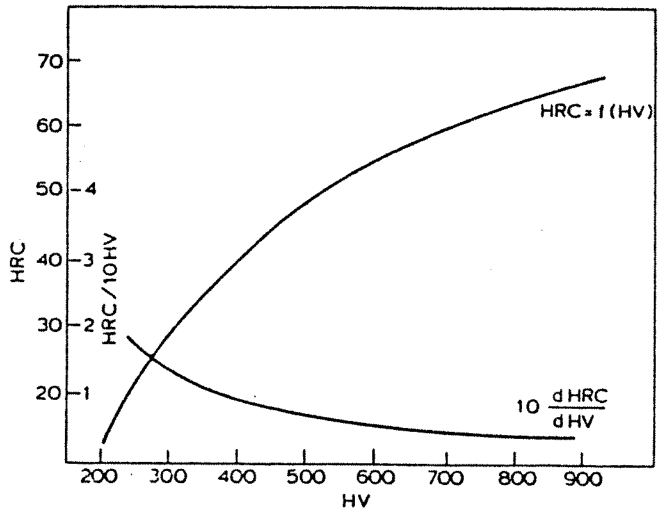


Fig. 76. Correlation between the HRC and HV hardness scales

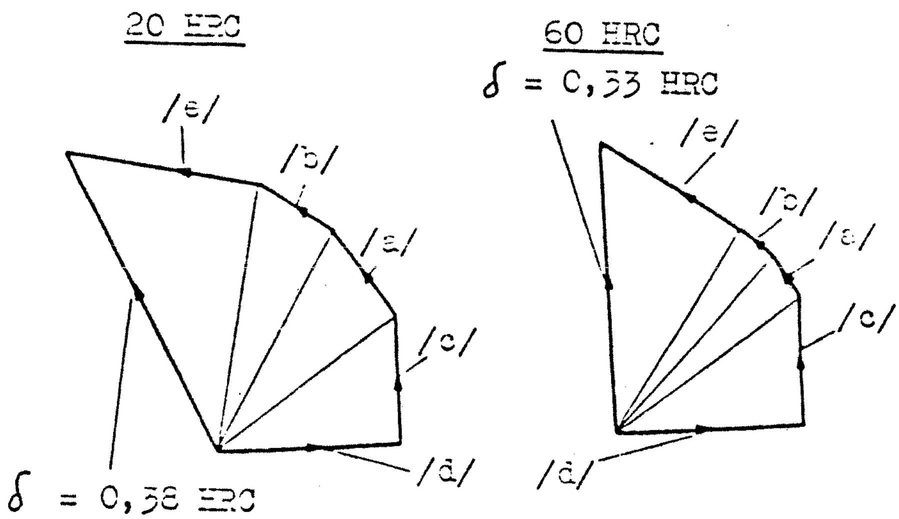


Fig. 77. Graphical addition of the factors of unknown systematic uncertainty

Hardness range	Control limits, in HR value
≥ 60 HRA	± 0.25
≥ 60 HRB	± 0.40
< 60 HRB	± 0.50
≥ 40 HRC	± 0.25
< 40 HRC	± 0.30
≥ 43 HR30N	± 0.60
≥ 36 HR30T	± 1.00

The control charts published by BARBATO [B-1] clearly show changes caused by mechanical modifications of the standardizing machine. E.g. the replacement of the anvil by another which was harder and had a better surface finish, has caused a systematic shift of the hardness scale by 0.1 HRC.

The control limits specified in Japan in [SR-52] for Vickers measurements are ± 0.8 % for HV 10 in the ranges 100-200 HV and 700-800 HV, and ± 0.5 % for HV 30 in the range 700-800 HV.

7.3. Unknown systematic errors

Systematic deviations and errors of a standardizing machine should be taken into consideration in two cases :

- If a higher order standardizing machine (e.g. international standard) exists, comparisons may establish a systematic difference. This can be used, with opposite sign, as correction with respect to the reference scale as maintained by the higher order standard. It should not be omitted, however, that the determination of the correction value has an uncertainty, which should be taken into consideration when stating the random uncertainty of the lower order standard.

- In the absence of a higher order standard, the standardizing machine should approximate the (ideal) test conditions laid down in the standard specification, as far as possible. In case of known deviations (e.g. in indenter geometry), corrections can be employed, as the effect of test conditions on hardness values is known from many research publications. (See the OIML Publication "Factors influencing hardness measurement" [P-21]). Prescribed (ideal) test conditions can be approximated, but measurement uncertainty sets limits to this approximation. The checking of the individual elements of the standardizing machine is performed with a certain accuracy, usually given by a range. The nominal values of test conditions, the "conventional true values" cannot be exactly ensured, we may have therefore an unknown systematic error of the standardizing machine. In calculating error propagation this can be included in the group of random uncertainties.

In the following the details of some methods for determining or estimating the unknown systematic deviations of Rockwell C standardizing machines from the "conventional true value" are described.

According to SMOLITCH [S-7] the range of uncertainty of Rockwell standardizing machine parameters was the following :

Preliminary test force	$\delta_{F_0} = \pm\ 0.01$ N
Total test force	$\delta_F = \pm\ 0.05$ N
Depth measurement	$\delta_e = \pm\ 0.2$ µm
Angle of indenter	$\delta_\alpha = \pm\ 0.08° \cong \pm\ 5'$
Radius of indenter	$\delta_R = \pm\ 2$µm

The effect of these factors on the measured hardness value was taken, partially based on [S-9] as given in Table 3.

Table 3

	Nominal hardness, HRC 25	45	65
$\frac{\delta H}{\delta F_0}$	0.13	0.08	0.03
$\frac{\delta H}{\delta F}$	- 0.04	- 0.03	- 0.02
$\frac{\delta H}{\delta e}$	0.5	0.5	0.5
$\frac{\delta H}{\delta \alpha}$	2.60	1.94	0.90
$\frac{\delta H}{\delta R}$	0.019	0.028	0.043

The propagation of these uncertainties can be calculated according to the formula :

$$\delta = \sqrt{\left(\frac{\delta H}{\delta F_0}\delta_{F_0}\right)^2 + \left(\frac{\delta H}{\delta F}\delta_F\right)^2 + \left(\frac{\delta H}{\delta e}\delta e\right)^2 + \left(\frac{\delta H}{\delta \alpha}\delta_\alpha\right)^2 + \left(\frac{\delta H}{\delta R}\delta_R\right)^2}$$

The calculation gave the following values for the unknown systematic deviation δ of the HRC standardizing machine.

$\delta = \pm\ 0.23$ HRC at 25 HRC
$= \pm\ 0.19$ HRC 45 HRC
$= \pm\ 0.15$ HRC 65 HRC

It should be noted that δ is the limit of a range with assumed uniform distribution. A conversion of this value is necessary if we intend to compose it with other uncertainty values given in the form of standard deviations ($s \cong 0.58\ \delta$).

The unknown systematic deviation (accuracy) of the Japanese HRC standardizing machine was determined by YAMAMOTO and YANO [Y-6]. The following factors and values were taken into consideration :

Preliminary test force	$\delta_{F_0} = 0.9\ \% \cong 0.9$ N
Total test force	$\delta_F = 0.2\ \% \cong 3$ N
Depth measurement	$\delta_e = 0.3$ µm
Angle of indenter	$\delta_\alpha = 5'$

Radius of indenter $\delta_R = 3 - 10\ \mu m$

The effect of these factors is shown in Table 4

Table 4

Factor	Hardness level, HRC 20	40	60	In Fig. 77
$\frac{\partial H}{\delta F_o} \delta_{Fo}$	0.12	0.07	0.05	(a)
$\frac{\partial H}{\partial F} \delta_F$	0.10	0.07	0.05	(b)
$\frac{\partial H}{\partial e} \delta_e$	0.15	0.15	0.15	(c)
$\frac{\partial H}{\partial \alpha} \delta_\alpha + \frac{\partial H}{\partial R} \delta_R$	0.22	0.22	0.22	(d)
Unknown factor	0.23	0.21	0.19	(e)
δ	0.38	0.35	0.33	

The quadratic addition of the individual factors is demonstrated graphically in Fig. 77.

In Table 5, δ corresponds to the confidence limits of 99.7 % probability at three repetitions. The correlation with the standard deviation for a single measurement is accordingly

$$\delta = \frac{3s}{\sqrt{3}}.$$

consequently $s \cong 0.58\ \delta$.

The unknown systematic errors of the Brinell hardness standard machine of the Soviet Union were determined as follows [B-15]. At Brinell measurements the factors force F, ball diameter D and indentation diameter d are considered as sources of systematic errors. Other test conditions (speeds, times, etc.) are considered as sufficiently stable. By partial differentiation of the definition equation of Brinell hardness, and by introducing several constants, we obtain for the unknown systematic error R the following formula :

$$\theta = \left| \frac{\Delta HB}{HB} \right| = \left| \frac{\Delta F}{F} \right| + 0.25 \left| \frac{\Delta D}{D} \right| + 2.25 \left| \frac{\delta d}{d} \right|$$

Maximum values of the individual error components, determined experimentally :

Force, $\Delta F/F$ 0.12×10^{-3}
Ball diameter, $\Delta D/D$ 0.40×10^{-3}
Indentation diameter, $\Delta d/d$ 1.17×10^{-3}

By substituting these values in the above formula for the propagation of errors, the unknown systematic error θ is found to be less than 3×10^{-3}.

Finally the values for the individual components of the unknown systematic deviation of the Czechoslovak hardness standardizing machines, published by ČUTKA should be cited. These form part of a scheme elaborated for all kinds of uncertainties therefore it is advisable to see the complete scheme in the next chapter. It should be noted that the Czechoslovak standardizing machines are not only national standards but are considered as international standards by a group of states of a region.

7.4. The system of uncertainties for the Czechoslovak standardizing machines [C-1, -5, -6, -7, -9]

Uncertainties of standardizing machines are classified in two main groups,
- definition of the hardness scale,
- reproduction of the hardness scale.

The uncertainties are stated as error limits (δ), which correspond to three standard deviations for the mean of 10 measurements. The components of uncertainty are the following :

δ_T definition of the scale

- δ_1 unknown systematic error of the test force
- δ_2 unknown systematic error of length measurement
- δ_3 unknown systematic error of the indenter
- δ_4 unknown factor

δ_{TT} reproduction of the scale

- δ_5 random uncertainty of test force application
- δ_6 reproduction of the group standard of indenters
- δ_7 uncertainty of length measurement (depth, diagonal, or diameter, respectively)
- δ_8 long time variation of the standardizing machine
- δ_9 variation of hardness on the surface of the test block.

These factors are composed by quadratic addition, namely :

$$\delta_T^2 = \delta_1^2 + \delta_2^2 + \delta_3^2 + \delta_4^2$$
$$\delta_{TT}^2 = \delta_5^2 + \delta_6^2 + \delta_7^2 + \delta_8^2 + \delta_9^2$$
$$\delta^2 = \delta_T^2 + \delta_{TT}^2$$

Values determined experimentally or by estimation for the individual components are given in Table 5.

Table 5

Uncertainty components of the Czechoslovak standardizing machines

($\delta = 3\,s_{\bar{x}}$, where $\bar{x}$ is the mean or 10 or 5 measurements)
(all values with sign ±)

	Rockwell C (HRC) with spiral microscope	Rockwell C (HRC) with laser interferometer	Rockwell N (HRN)	Rockwell T (HRT)	Vickers. (%)	Brinell (%) balls Ø10,Ø5	Brinell (%) balls Ø2,5
δ_1			0.01	0.01	0.01	<0.01	<0.01
δ_2	0.05		0.01	0.01	0.4	0.20	0.20
δ_3	0.30	0.30	0.20	0.02	0.2	0.02	0.04
δ_4	0.10		0.10	0.10	0.2	0.15	0.20
δ_T	0.32	0.30	0.22	0.10	0.36	0.25	0.29
δ_5	0.02	0.02	0.01	0.01	<0.01	<0.01	<0.01
δ_6	0.05	0.03	0.10	0.05	0.1	<0.1	<0.1
δ_7	0.08	0.02	0.02	0.02	0.05-0.25	0.20-0.35	0.25-0.45
δ_8	0.16	0.12	0.15	0.15	0.10-0.15	0.10-0.15	0.10-0.15
δ_9	0.06	0.06	0.08-0.13	0.13-0.18	0.3	0.2	0.2
δ_{TT}	0.20 (n=10)	0.14 (n=10)	0.20-0.23 (n=5)	0.20-0.24 (n=5)	±(1.3-0.16ln d [d in µm] (n=10)	0.25	0.36
δ	0.38	0.33	0.30-0.32	0.23-0.26		0.35	0.46

7.5. Other published values on uncertainty

The uncertainty values of the GDR hardness standardizing machines are stated [H-13] as follows :

Scale and range	Uncertainty u_{max}, in units of hardness (for n = 10 and P = 0.99) of reproducing the unit	of block calibration
62-82 HRA	0.16	0.30
60-100 HRB	0.20	0.37
20-66 HRC	0.14	0.26
71-92 HRN 15	0.28	0.50
45-82 HRN 30	0.20	0.35
25-72 HRN 45	0.20	0.35
65-85 HRT 30	0.35	0.60
100-450 HB	1.2	2.7
451-600 HB	1.8	3.6
200-800 HV	2.4	6.0

The head of the table indicates that the values are error limits corresponding to 2.58 times the standard deviation of the mean of 10 independent measurements. Uncertainty values for the same machines are given also in standard specifications [SR-55, -56, -60]. The wording used in the standard : "The uncertainty of transmitting the hardness value from the standard machine to the reference block (of block calibration) is characterized by the standard deviation s_{II} including the influence factors force, length and conditions of the test, and by the unknown error components Θ_{II}". These values are independent of the hardness level in the case of the Rockwell method, while in the case of the Vickers and Brinell method they are specified in function of the measured hardness value.

Specified values

Test method	s_{II} max	Θ_{II} max
Rockwell	0.05 HRA 0.05 HRB 0.05 HRC	0.15 HRA 0.25 HRB 0.15 HRC
Brinell	1.5 x 10^{-3} of HB value	2.5 x 10^{-3} of HB value
Vickers	1.5 x 10^{-3} of HV value	2.7 x 10^{-3} of HB value

The stated values of the Soviet hardness standard machines, as given in the standard specifications [SR-61 -62, -63] are the following :

Test method	Standard deviation, s	Unknown systematic error, Θ
Rockwell	0.1 HRA, HRB, HRC 0.2 HRN, HRT	0.3 HRA, HRB, HRC 0.6 HRN, HRT
Brinell	1.10^{-3} of HB value	3.10^{-3} of HB value
Vickers	1.10^{-3} of HV value	3.10^{-3} of HV value

The standard deviation indicated in the Table for Brinell standardizing machines was determined by the following method [B-15]. The surface of a block was divided into five equal fields. An indentation was made in each field. The mean of the five indentations represents one determination of the hardness of the block. The determination of the hardness was repeated 10 times. The standard deviation of ten determinations is less than 1×10^{-3} of the HB value (i.e. 0.2 HB and 0.6 HB, for the examined blocks of 200 HB and 600 HB, respectively). Accordingly the indicated standard deviation refers to the mean of five indentations.

Similar values are stated for the Bulgarian HRC standardizing machine [P-17]. The corresponding values for the HV standard are $s \leq 4 \times 10^{-3}$ of HV value and $\Theta \leq 8 \times 10^{-3}$ of HV value.

In the publication summarizing the technical data of hardness standardizing machines [P-17] the question concerning measurement uncertainty was formulated as follows :

- Specified data on the precision and accuracy of hardness reference scales realized by the standard machine.

The data supplied by the various laboratories are not uniform and often not sufficiently detailed, nevertheless it is worth repeating some of them as a basis of reference.

NPL Teddington states accuracy, as

"other dead weight machines conform within" ± 0.5 HRB
± 0.2 HRC
± 0.5 HRN, HRT
± 0.5 % HV

and precision as

"a calibration is reproducible to within" ± 0.5 HRB
± 0.2 HRC
± 0.5 HRN, HRT
± 0.5 % HV
± 0.75 % HB

from the mean value.

IMGC, Torino :

Repeatability on good blocks	0.05 HRC 0.3 % HV
Stability in one year on good blocks (obtained with the mean of 5 indentations)	0.14 HRC (hard end of the scale) 0.2 HRC (soft end)

MPA, Dortmund

Uncertainty of measurement	± 0.4 HRB ± 0.2 HRC ± 0.4 HRN ± 0.8 HRT

NRLM, Japan Confidence limits for n = 3, P = 0.95

0.40 HRA	at	60 HRA
0.35		70
0.30		80
0.80 HRB	at	40 HRB
0.70		60
0.60		90
0.40 HRC	at	20 HRC
0.35		40
0.30		60
0.55 HR30N	at	40 HR30N
0.50		60
0.45		80
1.15 HR30T	at	40HR30T
1.00		55
0.80		75
2.4 HV1	at	100-200 HV1
2.6		500
2.8		800
1.0 HV 10	at	100-200 HV 10
1.2		500
1.3		800
0.7 HV 30	at	100-200 HV 30
0.8		500
0.9		800

CSIRO, Australia

Accuracy : ± 0.5 HRA, HRC
± 1.0 HRB

Precision : ± 0.2 HRC
± 0.5 HRA
± 1.0 HRB

Uncertainty (at 99 %) ± 1 % of HV value (for diagonals above 150 µm)

Accuracy and precision are stated by a single numerical value in several Institutes :

Nat. Institute of Metrology, Beijing : ± 0.15 HRA, HRB, HRC
± 0.30 HRN, HRT
± 0.64 % HV
± 0.5 % HB

PKNJiM, Warsaw : ± 0.3 HRA, HRC
± 1 % HV

The total error (standard deviation) of the Japanese lever-type Brinell standard machine (Fig. 31) was stated [S-11] to be, with different magnifications and hardness levels :

Magnification	HB 160 ... HB 400
20 x	3 ... 6 HB
60 x	2 ... 3 HB
100 x	2 ... 3 HB

This total error can be decomposed to the error of producing the indentation and the error of measuring the indentation. The first mentioned component is responsible for 2 ... 3 HB.

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SR 15 ISO 674-1988 Metallic materials - Hardness test - Calibration of standardized blocks to be used for Rockwell hardness testing machines (scales A-B-C-D-E-F-G-H-K)

SR 16 ISO/R 1355-1970 Calibration of standardized blocks to be used for Rockwell superficial N and T scale hardness testing machines

SR 17 ISO 640-1984 Metallic materials - Hardness test - Calibration of standardized blocks to be used for Vickers hardness testing machines HV 0.2 to HV 100

SR 18 ISO 726-1982 Metallic materials - Hardness test - Calibration of standardized blocks to be used for Brinell hardness testing machines

SR 19 ISO 3534-1977 Statistics - Vocabulary and symbols

SR 20 International Vocabulary of Basic and General Terms in Metrology. BIPM - IEC - ISO - OIML, 1984

SR 25 OIML R 12 Verification and calibration of Rockwell C hardness standardized blocks

SR 26 OIML R 11 Verification and calibration of Rockwell B hardness standardized blocks

SR 27 OIML R 10 Verification and calibration of Vickers hardness standardized blocks

SR 28 OIML R 9 Verification and calibration of Brinell hardness standardized blocks

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SR 55 TGL 31542/06 Staatliches Etalon der Einheit der Härte nach Vickers (GDR)

SR 56 TGL 31542/07 Staatliches Etalon der Einheit der Härte nach Brinell (GDR)

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SR 61 GOST 8062-79 State standard and hierarchy scheme for hardness measurements on the Brinell scale (In Russian)

SR 62 GOST 8063-79 State standard and hierarchy scheme for hardness measurements on the Vickers scale (In Russian)

SR 63 GOST 8064-79 State standard and hierarchy scheme for hardness measurements on the Rockwell and Super-Rockwell scales (In Russian)

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