HARDNESS TEST BLOCKS AND INDENTERS

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PREFACE

Standardized hardness test blocks and indenters used for hardness testing are the subject of five OIML International Recommendations (No 9, 10, 11, 12 and 36). This synopsis is intended for those research workers who need more information than the specifications of an International Recommendation. Blocks and indenters are measuring means, the material and the production technique of which have a decisive effect on their application; therefore, some knowledge on them is very useful for the metrologist. Means and methods of checking are also discussed. Nevertheless, most space was reserved for the detailed survey of experimental results concerning the metrological characteristics of blocks and indenters.

The synopsis was compiled from journals, standards and reports published in different places and in different languages. It is assumed to be of special help to those metrologists who intend to start work on some detail problem of hardness measurement, especially for standardizing work, so that they should not be compelled to start everything from the very beginning; to show what others have already achieved, the results and sometimes the unsuccessful experiments of the older generations of reseachers.

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

The metrology of hardness scales. Bibliography, 1981,

Factors influencing hardness measurement, 1983.

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

An attempt was 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 has the possibility of studying the original publications in more detail, if necessary.

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

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Assistant Director

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1. The use of standardized hardness test blocks

Both hardness standardizing machines and industrial hardness testers are stationary devices, consequently their comparisons need a "transfer device" or "transfer standard" establishing the link between the higher and lower ranking measuring means. But even two hardness testers standing in the same laboratory beside each other cannot be compared, but by measuring the hardness of the same specimen, possibly that of the transfer standard.

This transfer device (or standard) is the standardized hardness test block. Standardized hardness test block should have

- a uniform hardness value along the surface, and in a sufficient depth,
- a hardness value constant in time, and
- characteristics permitting the determination of its hardness value with a minimum of uncertainty.

Use of standardized hardness test blocks was started in the 1930's [M-11]. The extent of their use can be characterized by two values : In the last decade 20-24000 blocks were produced in Japan in a year [Y-1, Y-2] . Of this number 40 % were for HRC, 17 % for HRB, 10 % for HV, 6 % for HB and 27 % for Shore hardness measurements. (For the European observer the value for Shore blocks is quite surprising). In the F.R. of Germany, between 1965 and 1975, in the average 11000 blocks were manufactured in a year [S-10]. Of these more than the half were Rockwell blocks, followed in decreasing order by Brinell and Vickers blocks.

A not secondary aspect of the effective use of the advantages of standardized hardness test blocks is that they should be permanently available in the market, in all the usual hardness values of all hardness scales.

2. Specified requirements for test blocks

Requirements for standardized hardness test blocks are specified in OIML International Recommendations No. 9, 10, 11 and 12 [SR-25, -26, -27, -28], in ISO International standards and Recommendations [SR-15, -16, -17, -18], and in various documents of regional international organizations [SR-36, -48, -49, -50].

2.1. Uniformity of hardness

The standardized hardness value of the blocks is defined as the arithmetic mean value of 5 indentations uniformly distributed over the whole test surface. (For Brinell blocks having a surface of more than 100 cm² [SR-28] specifies 8 indentations. According to [SR-27] for Vickers blocks the mean of 5 or 10 indentations should be calculated.) According to [SR-36] the calculated arithmetic mean should be rounded to 0,1 HR, 1 HV, or 1 HB for blocks of general use (II. Class), and to 0,05 HR, 0,5 HV, or 0,5 HB for blocks of special use (I. Class).

Uniformity of hardness of Rockwell blocks is calculated as follows. Let e_1, e_2 ... e_5 be the values in scale units of the measured increase in depth of indentation, arranged in increasing order of magnitude. The non-uniformity of the block under the particular conditions of standardization is characterized by

$$e_5 - e_1$$

and expressed in percent of $\bar{e}$,
where

$$\bar{e} = \frac{e_1 + e_2 + \ldots + e_5}{5}$$

In the case of Vickers and Brinell blocks let d_1, d_2, ... d_5 be the means of measured diagonals or diameters, respectively, arranged in increasing order of magnitude. The values $d_5 - d_1$ and $\bar{d}$ are obtained in a way analogous to that for the Rockwell blocks.

The specifications give maximum values for

$$\frac{e_5 - e_1}{\bar{e}} \cdot 100\ \% \quad \text{and} \quad \frac{d_5 - d_1}{\bar{d}} \cdot 100\ \%,$$

respectively. The requirements for Rockwell blocks specified by all organizations are identical, namely the maximum non-uniformity can be 1,5 % for HRC, 3 % for HRB, 2 % (or 0,6 HRN) for HRN, 3 % (or 1,2 HRT) for HRT blocks. For HRA blocks 3 % is specified in [SR-36].

In the case of Vickers blocks different organizations specify different values. In ISO 640 [SR-17] the following table is given.

Table 1

Hardness of block	Maximum permissible non-uniformity of d, % — HV 0,2 to less than HV 5	Maximum permissible non-uniformity of d, % — HV 5 to HV 100
< 225 HV	3,0	2,0
> 225 to 400 HV	1,5	1,0
> 400 HV	2,0	1,5

[SR-49] contains only the second column of this table, namely the one headed "HV 5 to HV 100".

[SR-27] specifies the same values as given in the column headed "HV 5 to HV 100" in Table 1, but for 10 indentations. If standardization is carried out by making 5 indentations, only 2/3 of these values should be taken (i.e. 1,3, 0,7, and 1 %, respectively).

[SR-36] employs only a classification according to the test force. The respective maximum permissible non-uniformity values are given as

HV 20 to HV 100	1,5 %
HV 10	1,8 %
HV 5	2,5 %
HV 3	3,2 %
HV 1	7 %

(An experimental justification of these values was given by KERSTEN and ECKARDT in [K-4].)

For Brinell blocks the maximum permissible non-uniformity according to most international prescriptions [SR-18, SR-28, SR-50] is 2 % for hardness values up to 225 HB, and 1 % above 225 HB. The CMEA standard [SR-36] gives maximum values independently of hardness, but depending on the 0,102 F/D^2 value, as follows

0,102 F/D^2 = 30	1.5 %
= 10	3 %
= 2.5	4 %

It should be mentioned here that the last mentioned standard differentiates between I and II Class blocks. The blocks specified by the other organizations correspond to the CMEA II Class. For comparisons of hardness standardizing machines blocks of the I Class are used with maximum permissible non-uniformity values equal to 2/3 of those for the II Class.

2.2. Stability of hardness

Some of the international documents specify the requirement for hardness stability. It is to be noted, however, that the applicability of this requirement is very questionable. How to check the stability of a measuring means during 2 years ? Most blocks will already have been used up during this period. At the initial verification the block is accepted if the other requirements are fulfilled. The stability requirement can be checked only on a sample taken from a lot of blocks, and if, after the elapse of two years, the blocks happen to be beyond the tolerance value, some action may perhaps be taken to change the material or production technology of the blocks to be produced later.

OIML International Recommendations [SR-25, ... -28] prescribe that the stability over a period of time of the hardness of the block must be such that, during the 2 year period between two successive periodic verifications, the hardness value of the block should not vary by more than the following values :

± 1.5 % of the initial HRC value
± 3 % of the initial HRB value
± 2 % of the initial HV value, below 225 HV,
± 1 % of the initial HV value, between 225 and 400 HV,
± 1.5 % of the initial HV value, above 400 HV,
± 2 % of the initial HB value, below or at 225 HB
± 1 % of the initial HB value, above 225 HB.

The corresponding values given in the CMEA standard [SR-36] are the following

± 1 %	of the initial increase in depth value (e) for HRC blocks
± 2 %	for HRA, HRB and HRT blocks
± 1.5 %	for HRN blocks
± 1 %	of the initial mean diagonal value (d) for HV blocks
± 1 %	of the initial mean diameter value (d) for HB blocks, if $0,102\ F/D^2 = 30$
± 2 %,	if $0,102\ F/D^2 = 10$
± 3 %,	if $0,102\ F/D^2 = 2,5$

2.3. Material

Standards give only general requirements concerning the material of standardized hardness blocks :

"The standardized blocks must be made of a material of which the homogeneity and the stability over a period of time (ageing) are known" (OIML), [SR-25, ... -28]. "The block shall be specially prepared and the attention of the manufacturer is drawn to the need to use a manufacturing process which will give the necessary homogeneity, stability of structure and uniformity of surface hardness" (ISO), [SR-18]. "It is recommended that the fineness and regularity of grain and the uniformity of the metallurgical structure be verified by microscopical examination. A microscopical examination may also be made by the standardizing authority. — It should be noted that the surface of the standardized block is necessarily work hardened by any machining and polishing process. It is necessary to ensure that the machining and final polishing processes are such that the work-hardening effects are uniform over the surface and do not penetrate to too great a depth" (ISO), [SR-15, -48, -49, -50].

"The standardized blocks shall be free of magnetism. It is recommended that the manufacturer shall ensure that the blocks, if of steel, have been demagnetized at the end of the manufacturing process" (ISO), [SR-18]. A numerical value of 2.10^{-9} Wb.m is specified for the remanent magnetic moment in [SR-36].

2.4. Geometry of the blocks, marking

The blocks may have a rectangular (square or oblong), triangular, or circular shape. According to [SR-36] the ratio of the two sides of the oblong should not be higher than 2:1. According to the same prescription, blocks prepared of bars of circular cross section should have a circular bore at the centre the diameter of which corresponds to 1/5 of the outside diameter of the block.

The block should have two parallel surfaces, one of which is the test surface, while the other the bottom (support) surface.

The minimum thickness of the blocks is given as 6 mm in all specifications. The only exceptions are the Brinell blocks for 5 and 10 mm ball diameter, the minimum thickness for which is 12 and 16 mm, respectively. In [SR-36] a special prescription is included for circular HRC blocks, which should be at least 10 mm thick.

The surface area of HR and HV blocks is specified only in the CMEA standard [SR-36] : 24 cm² at the maximum. The surface area of HB blocks is specified in several standards as follows :

Table 2

Ball diameter	ISO 726 [SR-18]	CMEA [SR-36]	EURONORM 128 [SR-50]
Ø 10	⩽ 150 cm²	⩽ 75 cm²	⩽ 150 cm²
Ø 5	⩽ 150 cm²	⩽ 40 cm²	⩽ 150 cm²
Ø 2,5	⩽ 40 cm²	⩽ 24 cm²	⩽ 30 cm²

The maximum permitted deviation in flatness of the surfaces is 5 µm. In the case of Brinell blocks this value can be increased to 20 µm in the case of ball diameters of 5 mm or higher, according to [SR-18 and SR-50]. For all Brinell blocks 10 µm is permitted in [SR-36]. In the OIML International Recommendation [SR-28] the permitted value is 25 µm for Ø 5 mm, and 50 µm for Ø 10 mm balls.

The maximum permitted error in parallelism of the two surfaces, measured at a length of 50 mm, is 0,01 mm for all HR, HV, and HB blocks for small balls. For the other Brinell blocks [SR-18 and SR-50] specify 0,04 mm, if the ball diameter is 5 mm, or more. In [SR-28] the requirements for ball diameters of 5 and 10 mm are 0,025 and 0,05 mm, respectively. For the same ball diameters [SR-36] specifies 0,02 and 0,03 mm, respectively.

Concerning the quality of the test surface the general requirement is that it should be free of scratches interfering with the measurement of indentations. Where numerical values are given, these are the R_a maximum surface roughness values for a sampling length of l = 0,80 mm (see ISO 468). The values prescribed by different organizations are not completely identical, as shown in the following table.

Table 3

Surface roughness, R_a µm

	HRA	HRB	HRC	HRN	HRT	HV	HB Ø 10 ball	HB Ø 5 ball	HB Ø 2.5 ball
ISO		0,2	0,2	0,2	0,2		0,4	0,4	0,2
OIML		0,3	0,3			0,1	0,3	0,15	0,15
CMEA	0,15	0,15	0,15	0,1	0,1	0,1	0,2	0,15	0,15

The bottom surface should be fine ground, with R_a = 0,8 µm [SR-17, -18], or R_a = 0,5 µm [SR-36].

To permit checking that no material has been subsequently removed from the surface of the standardized block, its thickness at the time of standardizing shall be marked on it to the nearest 0,1 mm (for Rockwell and Brinell blocks) or to the nearest 0,01 mm (Vickers blocks), or an identifying mark shall be made on the test surface. Beyond this each standardized block shall be marked with the following :

Arithmetic mean of the hardness values found in the standardizing test; name or mark of the supplier; serial number; name or mark of the standardizing authority [SR-15, ... -18].

The markings may be on the test surface or on the side surface of the block. In the latter case any mark shall be upright when the test surface is the upper face.

3. Manufacture of hardness test blocks

The manufacture of standardized hardness test blocks includes several complicated steps of material selection, heat treatment, and machining. The manufacturing technique is, of course, developing constantly towards shorter and less expensive processes. A paper published by FRANK in 1937 [F-3] mentions a special tool steel which was found suitable for blocks. To ensure a sufficiently stable hardness a careful artificial ageing was necessary, consisting of a stress relieving in oil bath of 180 °C for 200 hours, left lying for several weeks, followed by another treatment in an oil bath of 150 °. Later efforts were undertaken to simplify manufacturing processes, to reduce costs.

Some manufacturing processes were described by MITSUHASHI [M-23], OHWAKU and MIYASHITA [O-2], SMIRNOW [S-5, W-16], WOLKOWA [W-16], WOOD [W-17], YAMAMOTO [Y-1, Y-2], YOSHIZAWA and TERASAWA [Y-14].

These publications contain very valuable informations on the manufacturing of blocks. One should not forget, however, that the know-how may include many detail questions which cannot be learnt from published papers or which are guarded as production secrets.

To give a general image of manufacturing processes, a short summary of techniques described in the previously mentioned publications is given in the followings.

3.1. Material

Most blocks are made of plain carbon steel or of low alloy steels. As examples, the composition of some steel sorts used for block manufacture are given in Table 4 (Source : [W-17] for steel VII and X, and [Y-14] for the rest). Several other compositions, some of them used only for experiments, are mentioned in the references. From a practical aspect, it is advisable to employ the same steel for all the hardness levels, or at least for a wide range, by varying only the annealing treatment to obtain different final hardness values. E.g. in Japan the steel having the symbol III in Table 4 is used for producing blocks in the hardness ranges 20-60 HRC, 200-900 HV, 200-450 HB, while the range 60-67 HRC is covered by the steel V. [Y-2, Y-18].

For soft blocks non-ferrous metals (copper, brass, aluminium) are also employed. E.g. a 7/3 brass (70 % Cu, 30 % Zn) is used in Japan for the hardness ranges 30-95 HRB and 80-180 HV. Many details on non-ferrous block materials can be found in [Y-14], it should be noted, however, that non uniformity values do not reach those obtained on blocks made of steel.

The shape of the semi-finished material to be used can be plate, band or bar.

Table 4

Some steel sorts used for the manufacture of blocks

Composition %	I	II	III	IV	V	VI	VII	VIII	IX	X	XI
C	0,05-0,15	0,15-0,25	0,80-0,90	0,90-1,00	0,90-1,00	0,95-1,10	1,0	1,00-1,10	1,00-1,10	1,1	1,00-1,30
Si	0,15-0,40	0,15-0,40	< 0,35	< 0,35	< 0,35	0,15-0,35	0,2	< 0,35	< 0,35		< 0,35
Mn	0,30-0,60	0,30-0,60	< 0,50	< 0,50	0,90-1,20	< 0,50	1,2	< 0,50	< 0,80	0,4	< 0,50
P	< 0,035	< 0,035	< 0,03	< 0,03	< 0,03	< 0,025	< 0,03	< 0,03	< 0,03		< 0,03
S	< 0,040	< 0,040	< 0,03	< 0,03	< 0,03	< 0,025	< 0,01	< 0,03	< 0,03		< 0,03
Ni	–	–	< 0,25	< 0,25	–	< 0,25	0,5	< 0,25	–		< 0,25
Cr	–	–	< 0,20	< 0,20	0,5-1,0	1,30-1,60	0,6	< 0,20	0,5-1,0		< 0,20
W	–	–	–	–	0,5-1,0	–	0,4	–	1,0-5,0		–
Cu	< 0,35	< 0,35	< 0,30	< 0,30	–	< 0,30	–	< 0,30	–		< 0,30
Va							0,2				

A fine metallographic structure already in the semi-finished product is desirable, or it has to be ensured by a coarse grain annealing treatment. If a bar is used as starting material for disc shaped blocks the general practice is to prepare a centre bore to remove the portion of material where a good structure is difficult to ensure or segregations may arise. Disc shaped blocks without a centre bore were made from plate or band material.

Fig.1 shows an example of annealing the steel used as material for blocks. 1 denotes a period of keeping for 3-4 hours in the oven at 720-770°C. 2 is a cooling interval of 4-5 hours in the oven down to 350°C. 3 is the final cooling period in air. This treatment was employed for the steel having the symbol III in Table 3.

In the case of test blocks made of brass the refining of the crystallographic structure of the raw material can be ensured by a rolling mill operation. A 60 % reduction of the cross section is mentioned in [Y-14], followed by an annealing treatment.

3.2. Machining

The first machining operations serve not only to produce the necessary geometrical form (with the necessary allowance for later operations), but also to remove decarbonized or oxydized surface layers. Layers of approximately the same thickness should be removed from both faces of the future block. Cutting parameters and cooling media should be selected so as to prevent excessive heating of the material.

To ensure uniform stress distribution on the surface after hardening, disc shaped blocks are produced in Japan with a circular stress relieving groove having a depth and width of 0.5 mm.

3.3. Hardening

The hardening process should ensure a uniform fine-grained martensitic structure, without local soft areas of troostite or decarbonized and oxydized surface, further to prevent cracks or warping, with minimum and uniformly distributed internal stress. Since it is impossible to prevent completely the arising of internal stresses during hardening, all measures should be taken to reduce their extent both during quenching and immediately afterwards.

The blocs are heated to the required uniform temperature in a salt or cyanide bath. It is advisable to clean the bath before use with a regenerating salt to prevent stray matter adhering to the block surfaces and thus reducing the effectiveness of the quench over local areas. By reducing the acidity of the bath, oxydation and decarbonization of block surfaces can be prevented. Heating of the blocks is often realized in two steps. A pre-heat before reaching the final temperature may promote a simultaneous transformation to an austenitic structure in the whole volume of the block. The blocks are quenched in brine (sodium chloride in water) or in oil. To relieve stresses induced by the quench the blocks may be boiled in water.

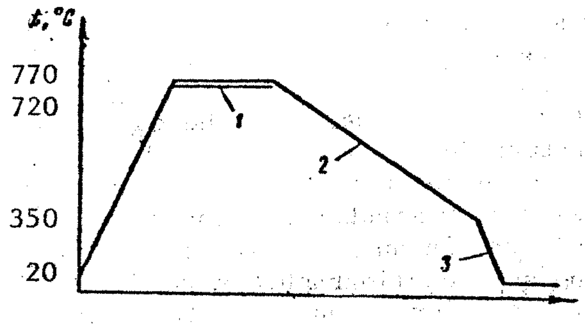


Fig. 1

Annealing process for a steel used for the manufacture of blocks

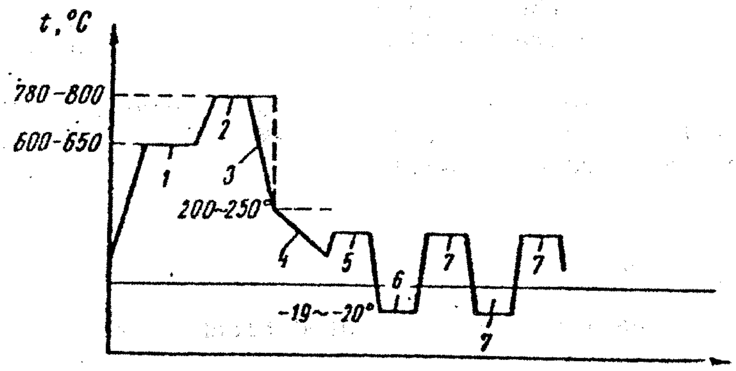


Fig. 2

Example of the hardening operation for a block material

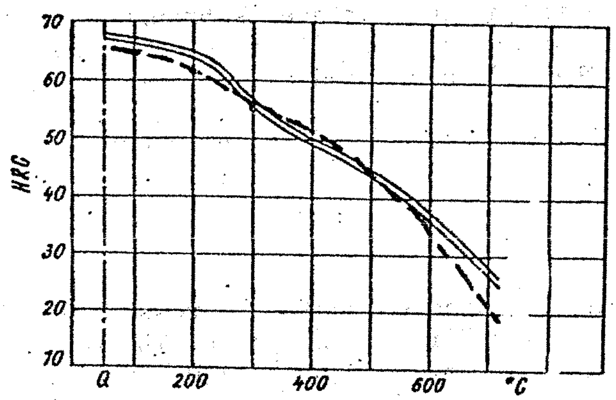


Fig. 3

Effect of tempering on the hardness of two steel sorts

From the numerous hardening processes employed for different steel compositions, a single example is shown in Fig.2. This hardening was employed for the steel having the symbol III in Table 3. In the figure 1 denotes a preheating for 1 hour at 600-650 °C. 2 is the period of maintaining the blocks at 780-800 °C for 5-6 minutes. 3 is the quenching in 4-5 % salt bath of 20 °C temperature during 5-6 s. From the temperature of 200-250 °C the blocks are cooled further in an oil bath of 60 °C, during 5-10 minutes (4). 5 denotes a 5-10 minutes boiling at 100 °C, followed by a cooling period during 5-10 min in an ice-salt mixture at - 19 to - 20 °C with the aim of stabilizing the metallographic structure of the steel. 7 denotes the repeating of operations 5 and 6, 3 to 5 times.

To obtain the required final hardness, the blocks are tempered in an electric oven at temperatures ranging from 100 to 700 °C.

The final hardness is determined primarily by the temperature of the oven. Fig.3 shows the effect of tempering temperature on resulting hardness. The double line represents steel sort III, while the broken line is for steel VII. To obtain a uniform tempering, blocks are kept 2-3 hours at the temperature corresponding to the required hardness, afterwards the oven is left to cool to room temperature together with the blocks being tempered.

Some manufacturers employ a low temperature treatment at - 77 °C, when most retained austenite is transformed to martensite, thus eliminating the main factor of long-time hardness instability.

3.4. Mechanical processing

The mechanical processing of heat treated blocks consists of grinding and lapping.

Wet grinding on a rotary surface grinder should be carried out by taking good care not to cause localized overheating of the material. The blocks are turned over frequently to compensate for initial bend produced during hardening and to remove the distortion arising as stresses are relieved during grinding. Flatness of the lower surface of the block is very important. A rocking block will enlarge Vickers indentations, while a block which flexes under load will not permit true depth measurement in Rockwell tests. Some technological parameters for grinding can be found in [W-17] and [S-5]. After grinding the surface is brought to bright finish by hand lapping or on an automatic lap. A final mirror finish, if required, especially for Vickers blocks, can be produced on a rotating polishing wheel.

The last operation in mechanical processing is demagnetization of the block.

3.5. Ageing

Mechanical processing may produce surface stresses, which may, in turn, result in ununiformity or instability of hardness. These stresses can be eliminated by artificial ageing, e.g. by keeping at 100-120 °C for 30-60 minutes, another at 130 °C for 24 hours. The treatment should be chosen in accordance with the given block material.

A detailed analysis of all the aspects of the heat treatment of a block material can be found in the paper of MITSUHASHI [M-23]. The aim of the research work was to establish the ununiformity of block hardness by varying heat treatment parameters for a steel containing 0,84 % C, 0,30 % Si and 0,42 % Mn. The effects of low temperature treatment were also examined.

4. Uniformity of hardness on the block surface

Individual points of the block surface may have different hardness values. To determine these differences, however, only a sampling procedure can be employed, since a hardness testing impression produced at a certain point makes that point unusable for further tests. Hardness test is a destructive testing, concerning a small area of the test piece.

Ununiformity of hardness on the block surface may result, first of all, from local differences of the metallurgical structure, from a deficient heat treatment or machining. The calibration (standardizing) of the blocks determines the hardness value of five (or ten) points on the surface. If the block has been produced correctly, the values of these five points are representative for the whole surface area of the block. But in the case of imperfections of material, of heat treatment or of machining, local deviations from the hardness values of the rest of the block may arise. One could reduce sampling uncertainty by increasing the number of indentations but the cost of calibration would increase and the value of the block is reduced, as the usable surface is reduced. Consequently the only reasonable solution is to find a perfect cooperation and interaction between production and calibration of the blocks. To find ways and means to detect production deficiencies from a small number of hardness tests. Sampling plans, control charts and other methods of quality control should be employed [G-3, S-10]. It is very important that blocks of the same production lot (blocks made from the same piece of raw material, by identical technology and within a relatively short time interval) be calibrated together. The importance of cooperation between the manufacturer and the calibrating laboratory cannot sufficiently be underlined.

When evaluating the results of calibration of a block, it should always be borne in mind that the uncertainty of measured hardness values includes two distinct factors : Test block variability, i.e. variability due to non-uniformity of hardness of the block, and machine variability, i.e. variability due to random errors in the indenting procedure and measurement.

To assess the true performance of hardness testing machines (including standard equipment as well), it is necessary to take into account the behaviour of test blocks in use, the sampling variability arising from the inevitable non-uniformity of the blocks and the environmental changes which may have occurred. Because a knowledge of the limitations of test blocks is fundamental to the whole scheme of maintaining hardness standard equipment and transferring their scales to other machines, the peculiarities of test blocks were examined by several research workers. Some of their results will be discussed in the following.

Most published reports concern the Rockwell and Vickers tests. Brinell indentations are much larger than those of the first mentioned two methods, therefore only a limited number of Brinell indentations can be applied on a block. Brinell blocks are used up much more rapidly. This may be one of the reasons of the relative scarcity of research results on the oldest of the three current hardness testing methods.

4.1. Type of distribution of hardness values

One of the fundamental questions for any statistical evaluation is the character of the distribution of individual values. Are measured hardness values purely random variables ? Have measured values a normal (Gaussian) distribution ? Most statistical tests are based on the assumption of a normal distribution.

YAMAMOTO et al. [Y-4] and ČUTKA [C-1] published some results of the "topography" of blocks, established by a large number of measurements (Figures 4 and 5). In many cases the points of identical hardness on the surface of the block form fields of concentric contours, in some cases of parallel contours, and on rare occasions hardness numbers do not follow any discernable system, they are really randomly distributed. (It has been proposed to name the line connecting points of identical hardness as "isohard", an artificial Graeco-English word, or "isoscler", composed of the Greek words meaning "identical hardness".)

ČUTKA [C-1] measured the hardness of the block shown in Fig.5 at 264 points, along 8 concentric circles designated by A to H. The number of indentations made on a single circle increases from 14 to 50 as we proceed from circle A towards H. The mean values for each circle are shown in Fig.6, together with the confidence limits (given as three standard variations). The overall mean of all points of the block is shown at the extreme right of the figure. The frequency of the occurrance of different hardness values was plotted in Fig.7 in two ways. The columns drawn by continuous line in the hystogram represent measured values. These can be replaced by the lower Gaussian curve. The hystogram drawn by dotted lines represents the case, when a correction was applied to measured hardness values to take into account the differences of mean hardness values along the individual circles (see Fig.6). This corrected hystogram can be represented by the higher Gaussian curve in Fig.7. On the basis of this analysis the hypothesis of normal distribution of values measured at different points was retained, with certain limiting conditions (e.g. applying indentations in certain zones).

YAMAMOTO [Y-4] has a different opinion : It cannot be assumed that the distribution of the hardness on the surface of a test block is normal, except in rare cases. Hence, even when test points on the surface of a test block are selected at random, the mean of the population cannot be estimated accurately. It is necessary to use some convenient method when a high degree of accuracy is required. (This method, namely dividing the surface into sectors, will be discussed later).

MARRINER [M-4, M-7] also shares the opinion that the distribution of hardness values over the test block is not Gaussian, the sampling variability from the test block contributes largely to the spread of measured values, even if blocks of better uniformity are selected for standardizing work, and the number of indentations is increased to ten, randomly disposed over the whole surface.

PETIK [P-11] performed a statistical test on the normality of 212 sets of measured hardness values. Each set consisted of 25 indentations applied at determined points within an area of 2 cm² on the block surface. (132 sets of HRC and 80 of HV 30 values). On the basis of the evaluation by a computer of the 212 sets, the hypothesis of a normal distribution of measured values could not be rejected at the 5 % level.

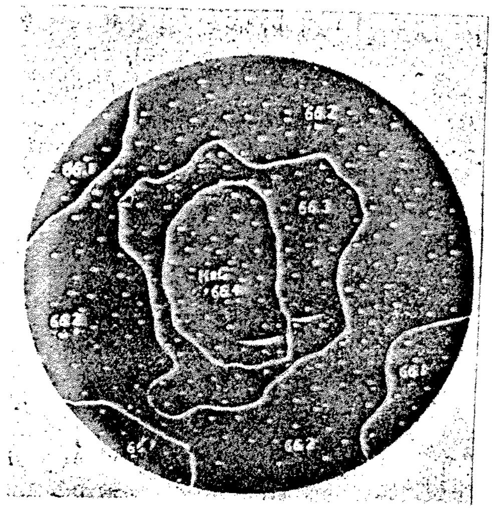


Fig. 4

Distribution of hardness values on the surface of a test block [Y-4]

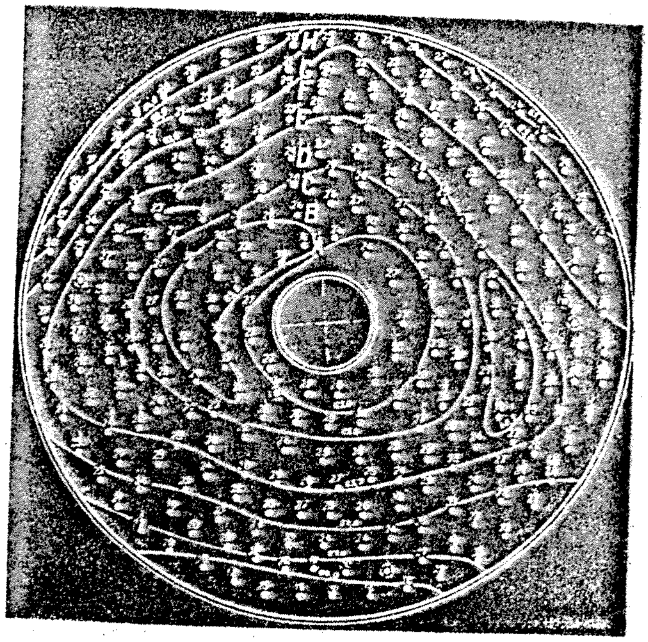


Fig. 5

Distribution of hardness values on the surface of a test block [C-1]

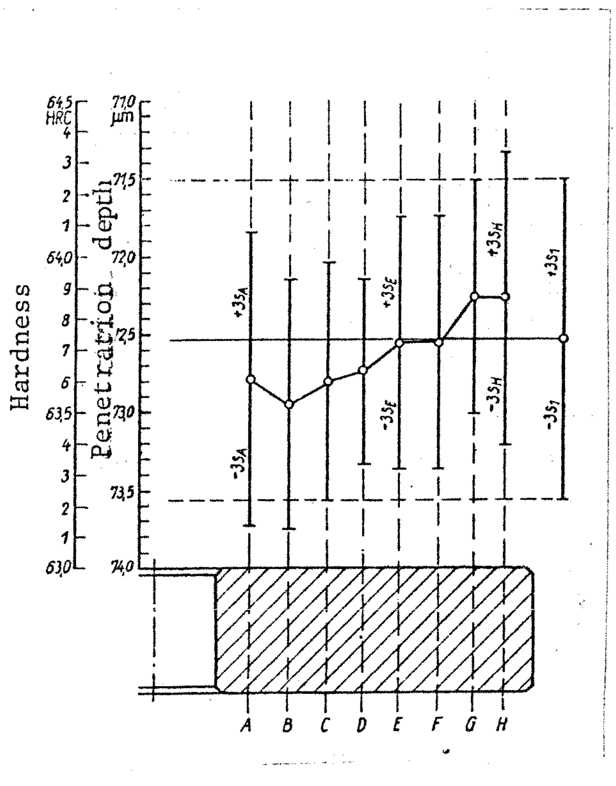


Fig. 6

Mean hardness values measured on the concentric circles shown in Fig.5

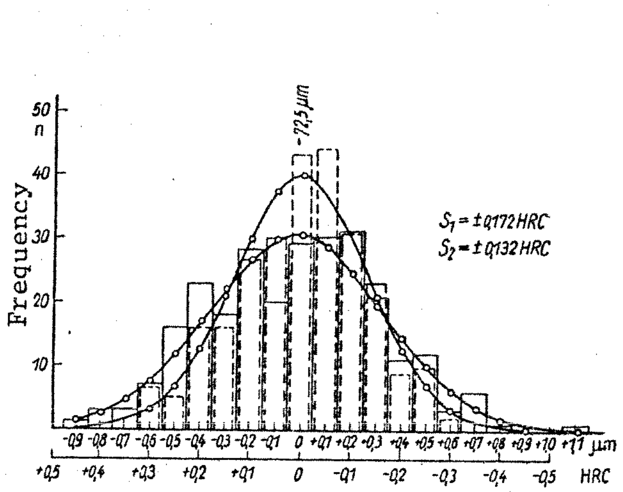


Fig. 7

Distribution of penetration depth values measured on the test block shown in Fig. 5

Four researchers were quoted here, of which two are for, and two against the hypothesis of normal distribution of hardness values measured on the surface of a standardized hardness test block. The question is disputed. Consequently some restrictions are to be employed, if necessary, at applying certain statistical methods for the evaluation of hardness standardizing measurements.

4.2. Experimental methods

Some methods of planning experiments are suited to reduce block variability.

YAMAMOTO, YANO and YAZIMA [Y-4, Y-5, Y-6] divided the surface of a test block into a certain number of small areas and a hardness test was made in each area at random order. In Fig.8a the division of the surface of a block to nine areas of equal surface is shown, formed by three concentric circles and three sections. (In other experiments five sections and three circles were employed.) Hardness values measured in each area are tabulated according to Table 5.

Table 5

Detection of systematic uniformity of hardness
on a test surface of a standard block

	Radial direction						
		1	2	3	$\bar{H}_{i.}$	$R_{i.}$	
Circumferential direction	1	H_{11}	H_{12}	H_{13}	$\bar{H}_{1.}$	$R_{1.}$	$\bar{R}_{i.}$
	2	H_{21}	H_{22}	H_{23}	$\bar{H}_{2.}$	$R_{2.}$	
	3	H_{31}	H_{32}	H_{33}	$\bar{H}_{3}$	$R_{3.}$	
	$\bar{H}_{.j}$	$\bar{H}_{.1}$	$\bar{H}_{.2}$	$\bar{H}_{.3}$	$\bar{H}$		
	$R_{.j}$	$R_{.1}$	$R_{.2}$	$R_{.3}$			
		$\bar{R}_{.j}$					

$$R_{1.} = \text{Max. of } (H_{11}, H_{12}, H_{13}) - \text{Min. of } (H_{11}, H_{12}, H_{13})$$

$$R_{.1} = \text{Max. of } (H_{11}, H_{21}, H_{31}) - \text{Min. of } (H_{11}, H_{21}, H_{31})$$

$$\bar{R}_{i.} = (R_{1.} + R_{2.} + R_{3.})/3$$

$$\bar{R}_{.j} = (R_{.1} + R_{.2} + R_{.3})/3$$

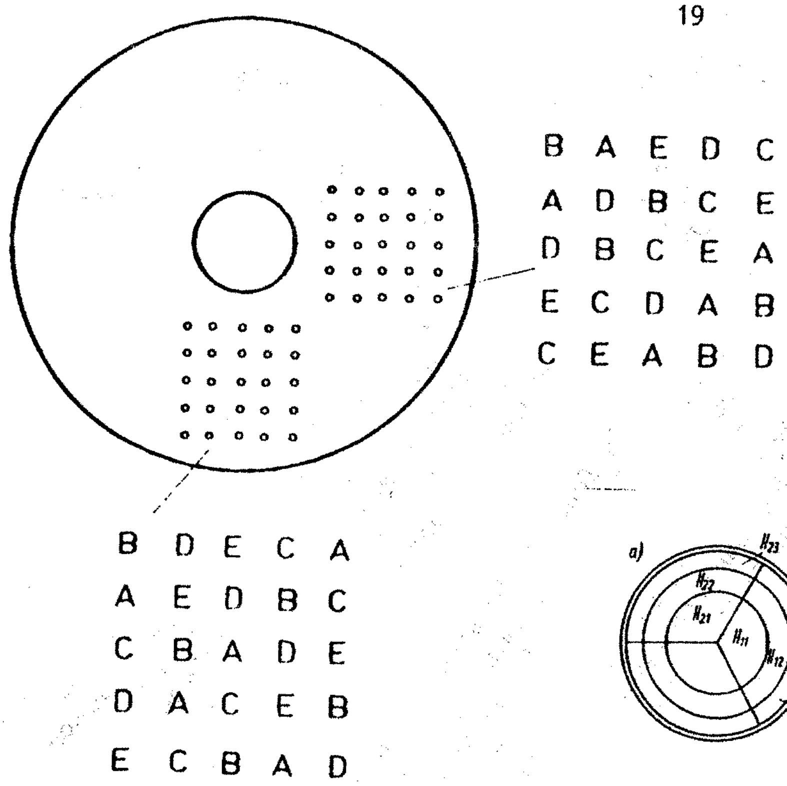


Fig. 9
Hardness testing indentations arranged in two 5x5 latin squares on the surface of the test block

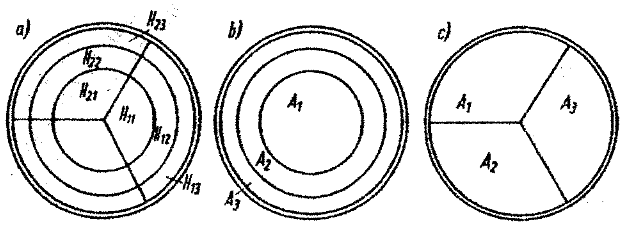


Fig.8. Division of the surface of a test block to sections, and circular areas.

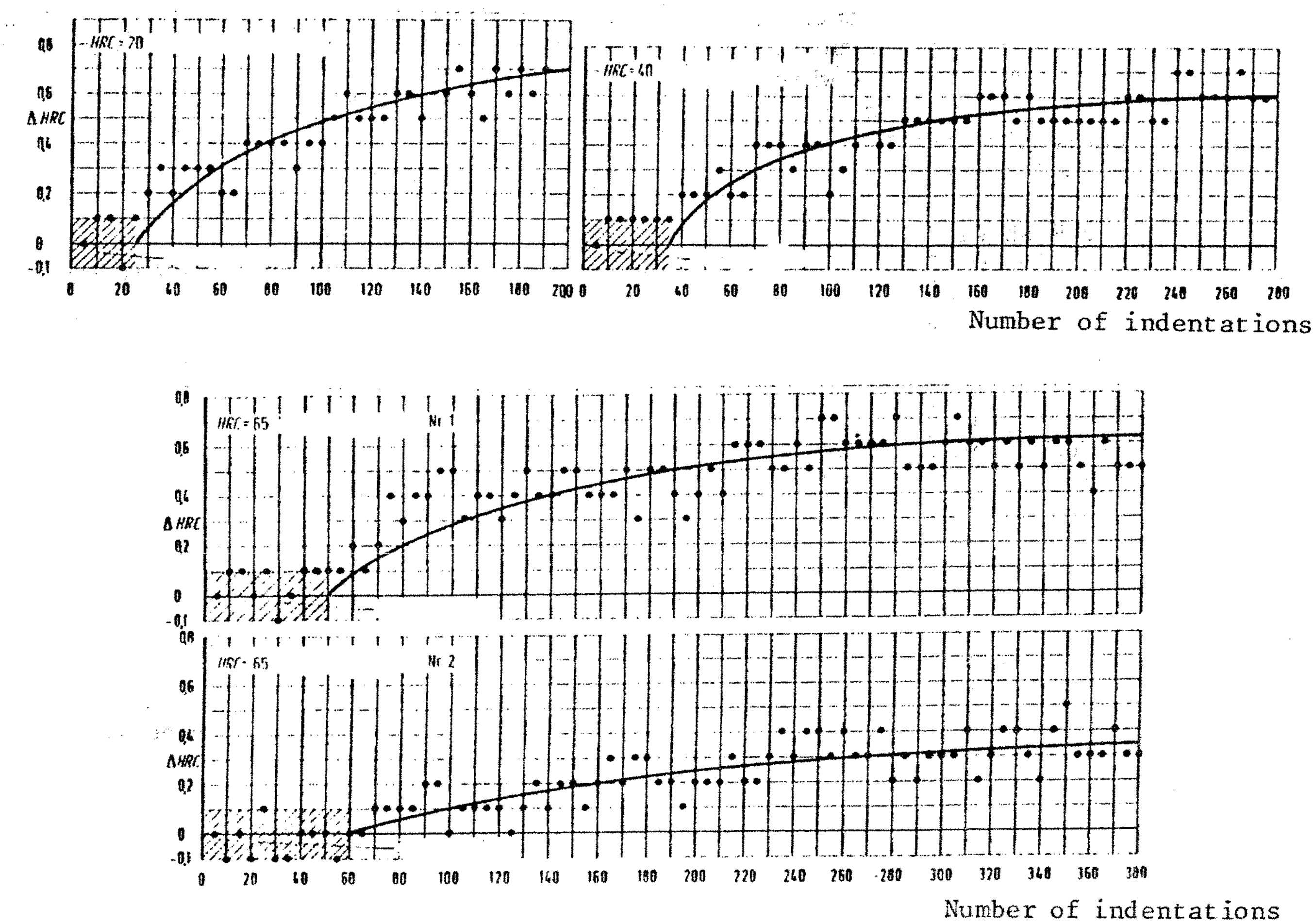


Fig.10. Hardening of blocks in function of the number of indentations.

Ranges of values in the individual sections and circles, and the averages of the ranges in both directions are calculated according to the formulae given under the table. Ununiformity in radial direction is significant if

$$\bar{R}_{i.}/\bar{R}_{.j} > 2.$$

In this case the block will be further used as shown in Fig.8b, the hardness of the three concentric ring or circle shaped areas will be stated separately.

If $$\bar{R}_{.j}/\bar{R}_{i.} > 2,$$

a significant ununiformity in the circumferential direction exists, in which case the block will be used divided into three sections according to Fig.8c.

The calculation given in Table 5 can be performed very simply. A more detailed analysis of the results can be performed, especially in cases when more than nine areas are formed and eventually several hardness tests are made in each area. In such cases an analysis of variance [Y-4] gives information on significant variations in the hardness of the block. Of course the desirable case is that no significant changes of hardness between different areas be found by the analysis of variance. In standardizing work, e.g. the international comparison of hardness standard equipment, the use of different areas of the blocks with different hardness values may be acceptable. In industrial practice, e.g. for the everyday checking of the correct functioning of hardness testing machines, the block should have a single hardness value.

Another experimental method for detecting local hardness variations on the test block surface is the arrangement of the indentations in latin squares. Employing this experimental methods, the aim of MARRINER [M-5] and PETIK [P-11] was to find an uncertainty value characterizing the variations of the hardness testing equipment, from which the variation of the block has been separated. Thus the latin squares, or in a more elaborate scheme the graeco-latin squares, indirectly give information also on the existence of significant variations of the hardness values at different points of the block surface.

Fig.9 shows a disc shaped block with central bore on which 50 indentations were made in two 5 x 5 latin squares. The five letters assigned to the individual indentations represent the five levels of another experimental factor (e.g. different indenters), but this is unimportant from the aspect of ununiformity of hardness of the block surface. The analysis of variance performed on 70 latin squares of HRC indentations gave significant local variations of hardness in one direction in 19 cases, and in two directions in 4 cases. Among 64 latin squares of HV indentations only 4 cases of significant local variations were found.

Of course, if an influence factor is found to be significant in an analysis of variance, this is always a relative statement. In our case local variations are significant with respect to machine and observer variations. If the same experiment, which was performed on hardness standard equipment, were repeated on industrial hardness testers, surface variability would not be significant at all. Or by improving the uncertainty of the standard equipment, more of the surface hardness variations would be revealed as significant.

4.3. Detailed pattern examination of blocks

The detailed examination of each block by the methods described in the preceding chapter is impossible, since the surface of the block is destroyed thereby, the block is used up. A detailed examination of blocks taken from a production lot, however, is necessary at the beginning of block manufacture and also later from time to time to verify constant level of production. Beyond this, the conditions of manufacturing should be continuously controlled statistically [Y-1]. STUPP [S-10] published some data also on the economic aspect, on costs of block calibration.

An examination method employed at the pattern approval of Vickers blocks was described by WOOD [W-17]. Three aspects were examined : hardness uniformity, metallurgical structure, and depth of uniform hardness.

To determine hardness uniformity and the variability due to sampling, many sets of ten indentations have been made on the blocks being under pattern examination. The minimum and maximum ranges observed, together with the average range were tabulated for several blocks, to be able to judge the suitability of the manufacturing process.

For the metallurgical examination of the hardened structure of a very hard block (over 900 HV) a particularly fine polish was obtained on the test surface which was etched, and then examined under a high-power microscope. It became evident that a block of uniform hardness showed only martensitic structure and that the presence of areas of troostite gave rise to inferior uniformity. The average hardness of the troostite areas was 924 HV, with a range of 902-939 HV, while the average hardness of the martensite areas was 943 HV, with a range of 940-949 HV. These ranges do not overlap. In such a case the individual points of the block surface do not represent a single population. If more than one metallurgical structure is present, it is unlikely that hardness values have a normal distribution. The same phenomenon was observed by LANGE and SCHIMMÖLLER [L-1] when examining the distribution of HV micro-hardness values on a steel surface (not a test block). The hystogram showed that surface hardness values represent two populations. Brinell indentations, in turn, cover a larger surface, not individual crystals, consequently measured HB values had a normal distribution.

Ununiformity of hardness in the depth direction on the block was also examined by WOOD in the pattern examination of HV blocks. This is of special importance if HV indentations with different test forces used to be made on the same block. The examination was carried out at five levels, each time grounding away a layer from the original surface. In the reported examination the first appreciable decrease in hardness occurred at a depth of about 0,76 mm below the usual test surface.

WOLKOWA [W-16] mentions a hypereutectic carbon tool steel used for hardness test blocks. Carbide particles of less than 2 µm diameter were counted at the microscopic examination. Table 6 gives the number of carbide particles on the surface of indentations produced by different hardness test methods. This indicates the importance of the uniform distribution of carbides, especially in the case of small indentations (e.g. HV 5).

Table 6

Carbide particles on the surface of

different indentations [W-16]

Hardness of the block measured by different methods	Surface area of indentation mm²	Number of carbide particles on the surface of indentation
61,0 HRC	0,170	4 590
857 HV 5	0,005	135
862 HV 30	0,032	865
865 HV 100	0,107	2 890

H. YAMAMOTO [Y-2], YOSHIZAWA and TERASAWA [Y-14] report on a Hardness Research Association group work in Japan, a sort of pattern examination, when several hundred blocks were measured by 10 indentations and the ranges were found to be considerably narrower than specified in the standards. To determine the effect of sampling of the block surface, a series of HRC blocks were measured twice by 5 indentations, after the elapse of a not specified time interval. Differences of mean values are reported to be less than 0,1 HRC.

5. Stability of hardness of the block in time

If the hardness of the calibrated test block changes in the course of time, this may have several reasons :

α) Metallurgical structure transformation. Such changes may occur even if the block is not used.

β) Mechanical effects, which can be either a "cold-work" hardening of the surface brought about by adjacent impressions, or an apparent change of hardness (of Rockwell blocks) on account of the not complete recovery of the elastic deformation of the block during the test process, if previous impressions have brought about a bending of the block.

Experimental determination of hardness stability in time is hampered by the fact that measured results include effects of the following factors which are difficult to separate :

a) Ununiformity on the block surface
b) Short time variations of block mean value (sampling variability)
c) Short time variations of the standardizing machine
d) Changes of block hardness on account of the mechanical effect of previous impressions
e) Change of block hardness in consequence of material structure changes
f) Long time variations of the standardizing machine
g) Variability of the measuring person.

Factors a) and b) were discussed in the preceding chapter. Research work in connection with factors d) and e), including attempts to separate the various factors, will be discussed in the following.

5.1. The effect of previously made indentations on block hardness

It is known from practical experience that the hardness of blocks is slightly increasing as more and more indentations are made as the block is "used up". This is the case even if the specifications for the minimum distance between indentations are observed. Several research workers tried to find the reason by time consuming experiments.

WEILER [W-9] tested 6 blocks of nominal hardness values 20, 40 and 65 HRC, respectively (2 at each level). Rockwell measurements were made until the free surface of the blocks was completely consumed. The arithmetic mean values of five indentations were calculated and plotted in Fig.10, as the deviation from the original hardness of the block in function of the number of indentations already made. In Fig.10 the values measured on one block of 20 and 40 HRC, and on two blocks of 65 HRC are shown. During the application of the first 30 to 60 indentations mean values remained within the shaded uncertainty band of ± 0.1 HRC. Hereafter measured values began to rise. The measured values are shown by dots in Fig.10 and the calculated regression curves seem to approximate some asymptote which was not reached, however, as there was no more place on the block surface. There was no significant difference between the hardening of soft and hard blocks, it is interesting to note, however, that the two blocks of 65 HRC showed a different degree of hardening. The non-uniformity of hardness within the groups of five indentations (HRC_{max} - HRC_{min}) were also evaluated but no significant increase in function of the number of indentations was observed.

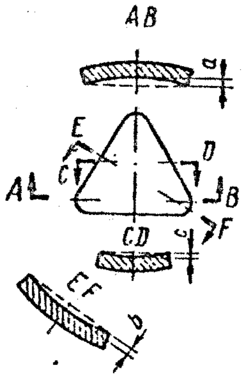
HORMUTH [H-12] determined the degree of bending of triangular blocks of 6 mm thickness after having filled the surface with indentations. Other details of the experiment were not published. The results obtained on different blocks are shown in Fig.11.

SMIRNOW and RODKEWITCH [S-13] continued this experiment with rectangular blocks of various thickness (6, 7, 8, 9 and 10 mm). All blocks had the nominal hardness of 61-62 HRC. It was found that bending is proportional with the number of indentations and inversely proportional with thickness of the block. The arithmetic mean of always 40 indentations, however, was independent of the number of indentations. The ununiformity of hardness values slightly increased with the number of indentations in the case of the 6 and 7 mm blocks, but no direct correlation could be established between bending and increase of ununiformity of hardness.

In another experiment SMIRNOW et al. [S-6] used 9 blocks of various hardness (levels of 25, 45 and 65 HRC), all having a thickness of 7 mm. After the application of 72 indentations the deviation of the surface of all blocks from flatness was higher than the specified tolerance value of 5 µm. The ununiformity of hardness increased with the number of indentations and exceeded the tolerance values after 72 indentations in the case of the 65 HRC blocks, and after 144 indentations for the 45 and 25 HRC blocks. Therefore increasing of the thickness of the blocks was proposed. This proposal, however, was not included in international standard specifications prepared since the publication of the report.

MARRINER [M-7] also found that an increase of hardness with use occurs with all HRC test blocks. Fig.12 shows in the first row the results obtained on four steel test blocks which were used for performance tests on indenters, the values plotted being the mean of five indentations at the periodic recalibrations with a master indenter. The horizontal axis indicates the number of indentations on the blocks and the vertical axis the increase in hardness value. The dimensions of the blocks were 64 x 44 x 10 mm. It can be seen that the increase of hardness was about 0,1 HRC at 67 HRC, increasing to about 0,3 HRC at 22 HRC per hundred indentations. To find the effect of eventual bending of the block, another depth measurement was made when the full load was still applied (beyond the two readings at preliminary load). The robust design of the NPL deadweight standardizing machine permits a depth measurement under full load which is unaffected by any distorsion of the machine. The measured values of depth D under full load are shown in Fig.12 in the second row. Depth increased with the number of indentations. If there had been no elastic bending of the block during the test cycle, an increase of depth would mean a decrease of hardness, but the obtained hardness values, as shown in Fig.12 increase with the number of indentations. Accordingly there must have been an increase of deviation of the block from flatness. In this experiment the hardness standardizing machine was actually used as a length measuring instrument to indicate the bending of the blocks at the effect of a load of 1373 N (140 kgf). Increase of bending, after having made a certain number of indentations, can be calculated by adding the two values shown in Fig.12 for the respective number of indentations. At doing this, hardness values should be converted to depth by employing 1 HRC $\hat{=}$ 2 µm.

A simple explanation of block hardening is that as Rockwell C indentations are made the material displaced by the indenter creates compressive stresses in the upper surface which are only partially relieved by block bend. The remaining stresses consolidate the material in the upper layers near the surface of the block and cause increased resistance to penetration under the full load so that the hardness value increases.



a	b	c
μm		
23	22	16
15	16	13
12	13	10
11	12	10
17	20	15
9	10	8

Fig.11. Measured bending of several blocks after being filled with indentations.

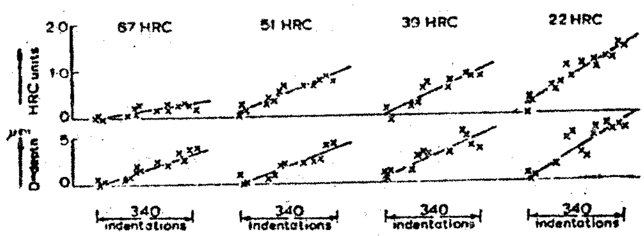


Fig.12. Increase of hardness value and of indentation depth characteristics with the number of indentations made.

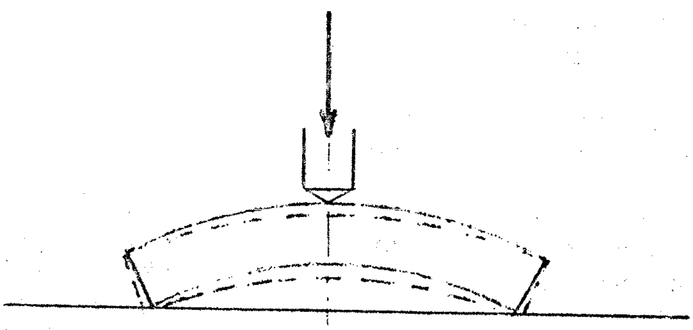


Fig.13. Bending of the block under the test load.

That these conclusions are probably correct is confirmed by noting that thick blocks, which bend less, increase in hardness more rapidly. In addition, it has been noted that if a used test block, which has increased in hardness and is bent, is relapped on its bottom surface, the stresses in the upper surface are relieved by further bending and the hardness of the upper surface returns to its original value [M-4].

A manufacturer asked NPL to recalibrate periodically five test blocks being used to control the Rockwell C scale traceable to the national standardizing machine. Between each calibration by NPL the manufacturer made one hundred indentations in day to day checks on his machine. The hardening of the blocks was in agreement with values given in connection with Fig.12. The change was linear, i.e. the same amount of hardening occurred between the 1st to the 100th, as between the 101st to the 200th indentations. (Higher degrees of using the blocks were not mentioned).

Although the results shown, together with the suggested explanation, are a fair assessment of the behaviour of test blocks in the Rockwell C test, and are confirmed by results with the Rockwell B test, it is evident from other work that the changes which occur in the surface metal when indentations are made is extremely complex. For example, maintenance work with the Vickers test does not reveal the same block hardening effect and in fact, from results with different loads on the same blocks, suggests that the blocks become increasingly surface soft, i.e., the non-uniformity of hardness in depth increases. Because the volume of material displaced is small in comparison with the Rockwell C test the effects are not apparent until hundreds of indentations have been made but an effect of this nature, if it exists, is not incompatible with the previous results as surface softness increases the hardness value in the Rockwell C test. (The depth of penetration under preliminary load is in such a case greater, the datum line is depressed.) Whatever the true explanation may be this difference in behaviour of test blocks lends emphasis to the fact that the Vickers and Rockwell hardness tests are fundamentally different and that, in particular, they are influenced quite differently by the non-uniformity of hardness in depth which exists in most test blocks or material under test.

These questions can be better understood on the basis of a report by YOSHIZAWA [Y-14] on research work in Japan in connection with the effect of residual stress in the block. Compression stress increases, tension decreases hardness. Tests were made on steel sheet metal with 0,44 % carbon content. The hardness values obtained under different stresses were found to be

138 HV at 150 N/mm² tension
142 HV without stress
145 HV at 50 N/mm² compression.

The same trend was observed on blocks made of steel for roller bearings. These experiments explain practical experience discussed in the preceding.

The effect is greater if the block was already bent in consequence of material displacement due to indentations. Fig.13 shows the scheme of a bent block. Under the test load the bent block is flattened out, the new shape is indicated by dotted lines. In this position the test surface is subject to additional compressive stress what results in increased hardness, in conformity with experimental data presented earlier.

YOSHIZAWA and his colleagues found a smaller increase of hardness if the block is thicker. This shows that compression stress brought about by bending is more important than that caused by small material displacements. Increase of hardness at the centre of the block was greater than near the circumference.

5.2. Maximum number of indentations on the block surface

ISO Recommendations and Standards on hardness testing methods [SR-1, SR-4, SR-8] specify the minimum distance between the centres of two adjacent indentations as four times the mean diameter of the Rockwell or Brinell indentation, and three times the mean diagonal of the Vickers indentation, respectively, in the case of steel specimens. These prescriptions apply for ordinary hardness tests performed in everyday practice. For standardized hardness test blocks the Japanese Hardness Research Association [Y-2, Y-14] recommended the following values, as the maximum number of indentations for a block of Ø 64 x 15 mm :

500	at	60 HRC
260	at	30 HRC
250	at	90 HRB
190	at	60 HRB

This density number of indentations per unit surface is about the half of that recommended by ISO for current hardness tests.

The NRLM of Japan [Y-17] specified the limit number of indentations which may cause hardness changes of 0,1 HRC at the maximum. For blocks having dimensions of Ø 60 x 15 the numbers given are

200	for	60 HRC
150	for	40 HRC
100	for	20 HRC.

This density corresponds approximately to one fourth of the ISO specifications.

For checking the stability of national hardness standardizing machines in the N.P.L., MARRINER [M-7] applied less than 100 indentations on a block, in which case a block hardening effect was hardly noticeable.

This statement is not valid for all types of blocks. The number of indentations applied on a block in the experiments to be discussed in the following chapter was only 60/year. Nevertheless a definite hardening was observed already during the first year of the experiment, and this was even higher than in later years.

5.3. Experiments to establish long time variability

Experiments to be discussed in the following are related to those discussed previously, but they include a longer period of time, namely several years. Measurement results include the effect of previously made indentations, the long-time variations of the block and those of the standardizing machine. The separation of these factors would be very important. It should, however, be emphasized at the beginning that it is nearly impossible to deduce generally valid numerical results from such experiments, which last half a decade or so, and the results are always connected to the given type of blocks. There is no proof that the results apply also for blocks of other make, or even to blocks of the same type but taken from another production lot, eventually after the elapse of several years. Results should therefore be utilized rather qualitatively, the numerical values only as orders of magnitude.

A set of five HRC blocks of different hardness levels were examined by PETIK [P-8, P-18, P-20] during four years. The surface of the blocks was divided into five sections. In each section one indentation was made each month. The mean of the five indentations made at once on a block was plotted in function of time. For the sake of not being lost in details, Fig.14 shows only the mean values for each year (circles), the mean for the four year period (crosses), the regression lines representing the monthly values during one year and the regression line for the four-year period. For the mean values the uncertainty values (± 2 s) are also shown.

The four-year regression lines are all rising, the slope being inversely proportional to hardness. But the yearly regression lines are sometimes rising, sometimes descending. The general pattern is rising or nearly constant in the first two years, followed by descending sections later, as best shown by the soft block. The changes of the 32 HRC block however were different, years of rising and descent alternating. The standard deviation values around the four year mean were ± 0,11 ... 0,32 HRC. This value represents the variation of the means of five indentations. (To obtain the standard deviation of a single hardness measurement, a multiplication by $\sqrt{5}$ is necessary).

The results of this experiment can be summarized so : The long-time variation of the standardizing machine and of the given blocks can be characterized by an uncertainty value, which changes from 0,25 to 0,70 HRC as we go from the hard to the soft end of the HRC scale (standard deviation of a single measurement).

The experiments on the same standardizing machine were continued by KOVÁCS [K-15]. To detect eventual differences of blocks of different origine, blocks from two different countries were measured in parallel during three years. (For the hardness levels 51 and 23 HRC only one block was used). The frequency and number of indentations were the same as in the previous experiment. Fig.15 shows the six-months' mean values in function of time. The blocks of the two hardest levels (I and II) did not show a hardening effect. If we compare the three pairs of blocks of different manufacturers for the same hardness level (I, III, IV) we can see some increase of difference between them as time goes on. The type of block shown by a continuous line has a trend of hardening, especially at lower hardness levels. (This block is of the same manufacture as those the results of which are given in Fig.14). The other type of block (indicated by dotted lines) is more stable in time. At 65 HRC it even shows a slightly softening character.

The experiment was continued and further refined by KOVÁCS [K-15] in cooperation with KERSTEN. In the four year period 1978-1981 five hardness test blocks (20, 30, 40, 50, 60 HRC nominal) were measured by five indentations each month at the laboratory of OMH, Budapest. To detect eventual fluctuations of the standardizing machine, the same blocks were measured in the same period also in the laboratory of ASMW, Berlin, 2 to 3 times in a year, on 11 occasions in all during the four years. The 48 and 11 measured values, respectively, were represented by a calculated regression line.

Results of the experiment : All the regression lines are rising, i.e. a steady hardening of the blocks was observed. The rate of hardening was greater at the beginning of the experiment. The degree of hardening during four years is inversely proportional to the hardness level. Fig.16 shows the values of the increase of hardness during four years as observed by the two laboratories.

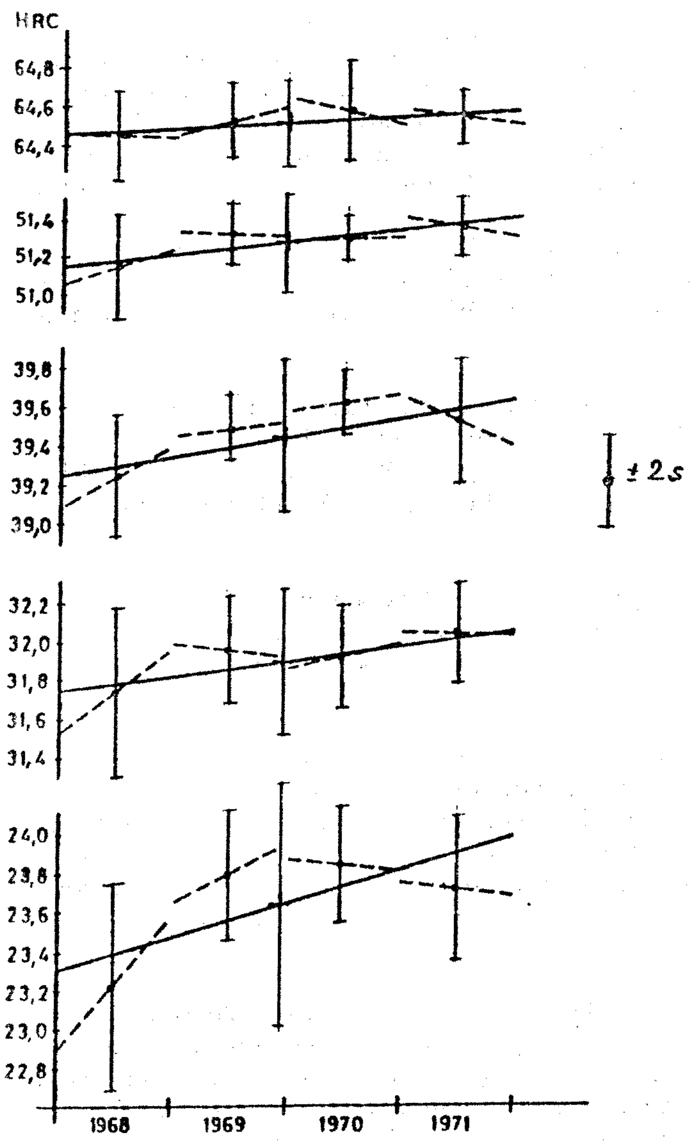


Fig. 14

Long-time variability of five Rockwell C blocks.

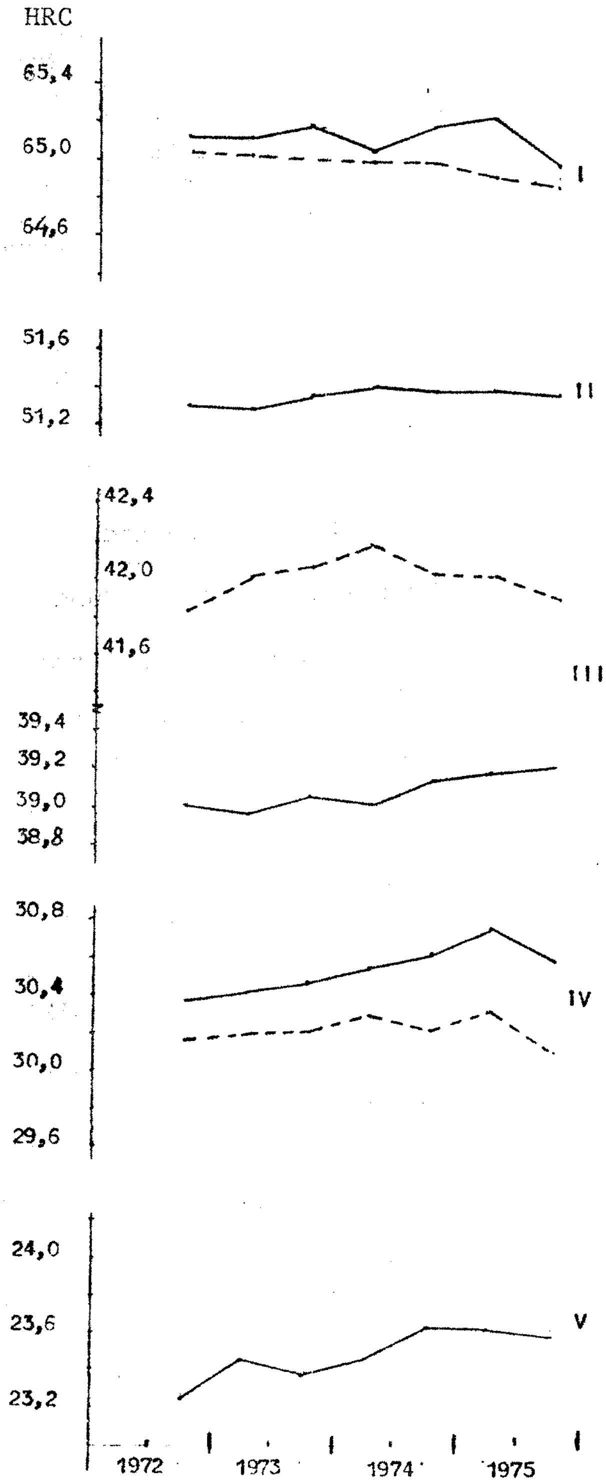


Fig. 15

Comparison of the long-time variability of Rockwell blocks of two manufacturers.

The four-year regression lines of the two institutes coincide well for all the blocks, the hypothesis of there being no difference between them cannot be rejected at the probability level of 99,9 %. By examining the change of measured values from one month to another, mostly changes of 0,1-0,2 HRC were observed. In some cases, however, especially on the lower part of the hardness scale, unexplainable monthly changes of 0,5-0,7 HRC were also found.

In summarizing, it can be assumed that the changes observed during this last series of experiment can be clearly attributed to the blocks. The parallel measurement on two standardizing machines eliminated the machine effect.

This kind of long-time checking of the HRC standardizing machine, together with comparisons in longer intervals (3-4 years) with the international CAEM standard equipment (at ČSMU laboratory in Prague, Czechoslovakia) is considered to be sufficient for maintaining the National HRC Hardness Reference Scale of Hungary.

A subject for future experiments, or at continuing this series of long-time tests could be the elimination of the effect of the bending of the blocks, discussed earlier. This could be done by relapping the bottom surfaces of the blocks each time before starting the periodic recalibration.

MARRINER [M-4] too is of the opinion that if HRC test blocks having the ununiformity of hardness specified in standards, or selected ones with a better range of values are regularly calibrated in a standardizing machine to determine that it is maintaining a constant scale of hardness, there is a high probability that any change observed may be due to test block variability and not to the standardizing machine. This opinion is shared by YAMAMOTO, YANO and YAZIMA [Y-4] too.

For the Vickers scale maintained at the N.P.L. two typical results embracing a five year period are shown in Fig.17 [M-4]. It is not easy to determine how much of the variability shown is due to test block variability, observer variability when reading the measuring microscope, and variability of the indenting machine. Experience of repeatedly calibrating blocks of different uniformity leads to the belief that variability of the indenting machine contributes very little to the spread of values shown in Fig.17. The major difficulty of maintaining and transferring a Vickers standard is to be found in the test blocks, the measuring microscopes and observers. Measuring microscope and observer are sources not only of variability, but also of bias.

5.4. Change of hardness in time on account of structural changes

Very few data were published on the subject. The solution of this problem is a task mainly for the manufacturer, consequently if structural changes occur in some hardness test block, it does not deserve to be named a standardized test block. Such problems should come to the fore at the manufacturer's or, at the latest, during pattern approval of the block.

YOSHIZAWA and TERASAWA summarized in [Y-14] the results of collective experiments performed in Japan. The importance of the correct selection of material, of production technology and heat treatment are emphasized.

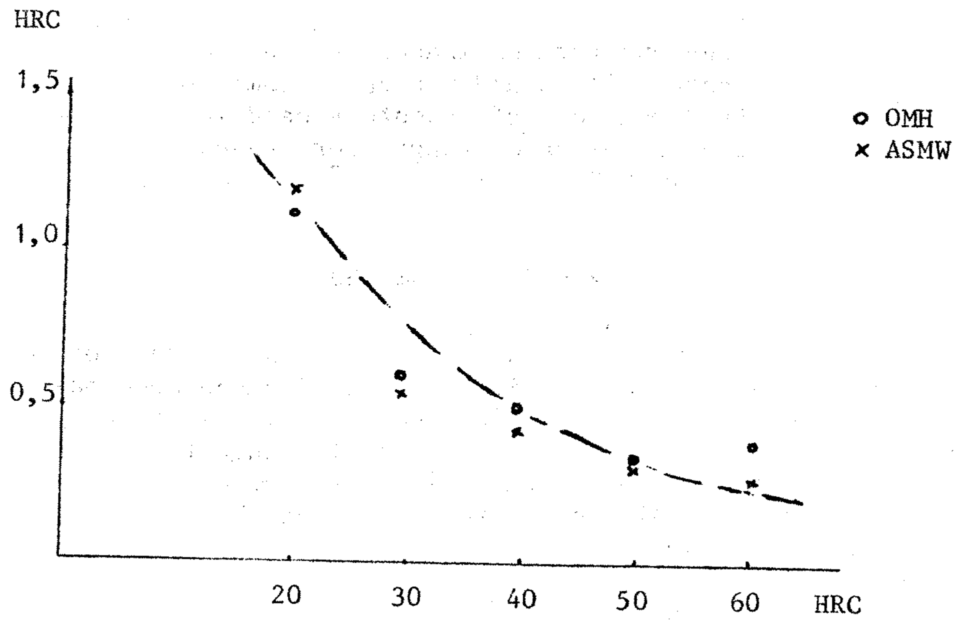


Fig. 16

Increase of the hardness of five Rockwell blocks as observed by two laboratories.

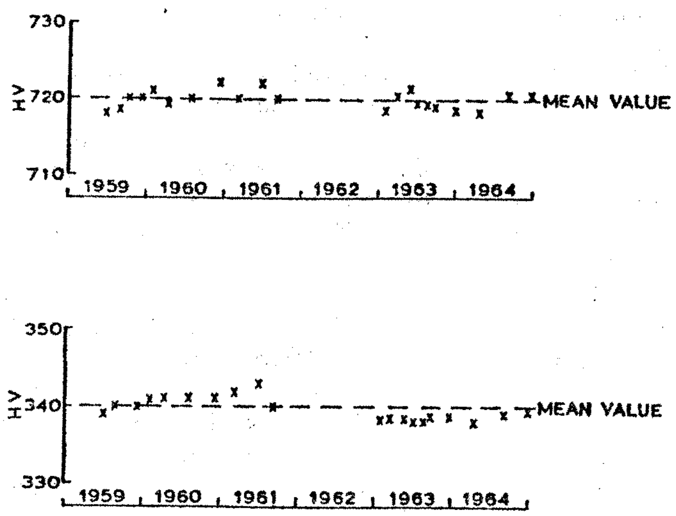


Fig. 17

Variability of Vickers blocks

For MARRINER [M-4] secular changes in the test blocks did not appear to be a major difficulty. Test blocks tempered at 100 °C or above have been used at the N.P.L. for long-term maintenance work and have given no indication of changing in hardness. However, there is some evidence that a fully hardened block, which has received no subsequent heat treatment, may decrease in hardness by about 1,5 per cent of the mean hardness value over a period of five years and such blocks are unsuitable for maintenance work.

6. Specified requirements for hardness testing indenters

An essential part of the conventions on hardness testing methods concerns the design and form of indenters. The geometry of indenters is prescribed in standards. All standards and recommendations listed in the References specify dimensions of indenters used in ordinary hardness testing equipment. Reduced tolerance ranges for standard hardness measuring equipment are specified in [SR-37,-48,-49,-50].

6.1. Diamond cone [SR-1,-11,-12,÷24,-37,-45,-48,-50]

The Rockwell-C,-A and -N indenter is a diamond in the form of a right circular cone with a rounded tip (Fig.18). The diamond cone has an included angle of 120°. The tip of the cone is spherical with a radius of 0,200 mm. The surface of the cone should blend in a truly tangential manner with the surface of the spherical tip (at the points indicated by heavy arrows in Fig. 18 where specified tolerances are also given. The values in brackets apply for standard equipment.

For the radius of the spherical tip the ISO Recommendation [SR-11] which is being revised now specified the tolerances in another form (Fig.19). According to this prescription, the contour of the whole of the tip should not depart by more than 0,002 mm from the theoretical profile. This specification was much disputed and will be omitted from new standards. Though it first seems very convenient for checking the projected image against a master screen but it is not unequivocally defined that the prescription applies only for the spherical part of generatrix of the indenter and not for the cone. Beyond this, by employing the method shown in Fig.19, it is in principle possible that a radius approaching zero (pointed cone) be accepted.

WOOD et al. (W-21) evaluate maximum, minimum and mean radius separately, when different values are obtained in different axial sections of the indenter.

Diamond indenters must be polished over a surface area such that, when the indenter penetrates to a depth of 0,3 mm, no unpolished part comes into contact with the material being tested. The polished surface must be free from defects, cracks and wear.

The diamond cone must be mounted firmly in the holder. Cone axis and holder axis should be in line within 0,5° (0,3° according to SR-48). The design of the holder must ensure that it remains firmly fixed in the hardness testing machine even under the action of the maximum permitted test force. When the holder is fitted with a shank, the shoulder at one end of this shank must be flat and perpendicular to the geometrical axis of the mount. Rockwell C indenter holder dimensions for a hardness standard machine are shown in Fig.20.

Beyond the specified values, various other characteristics of indenter geometry may also influence hardness value[W-21]. So e.g. the roundness of the cone (circular cross section in planes perpendicular to the axis), rectilinearity of the generatrix of the cone, and especially surface quality of the diamond. The anisotropy of diamonds makes difficult the machining of the indenter to a precise symmetrical form.

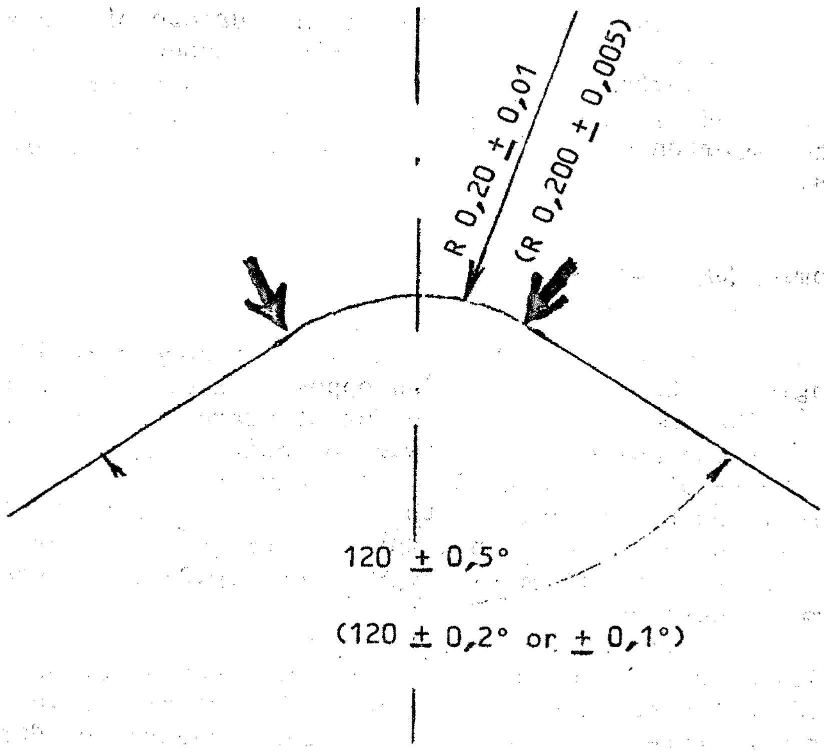


Fig. 18

Specified geometry of Rockwell cone indenters

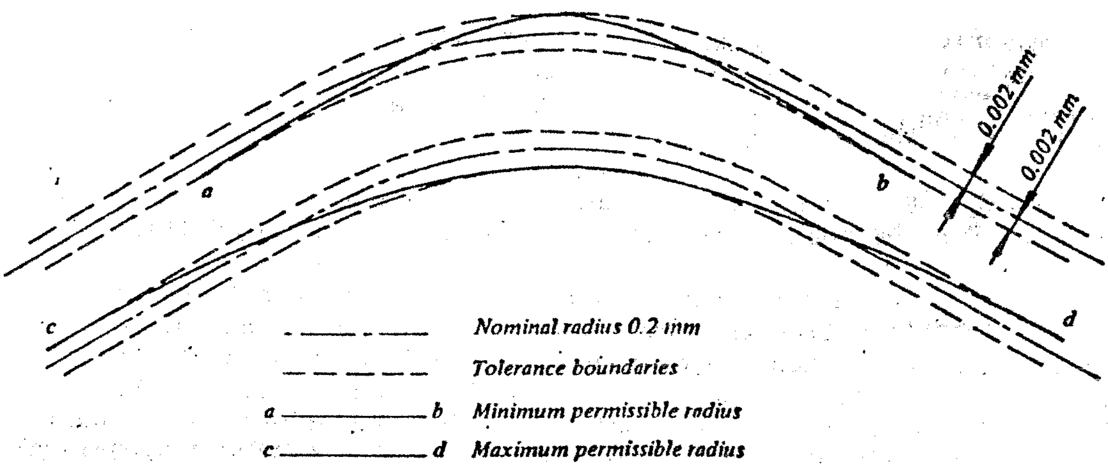


Fig. 19

Tolerance band of Rockwell cone indenters
as specified earlier.

Small cracks, pits or other flaws in the surface of course influence friction between indenter and tested material, consequently measured hardness value as well. And surface faults may cause a rapid deterioration of the indenter with steadily changing hardness indication. One cannot sufficiently emphasize the importance of indenter characteristics not expressly specified in standards.

6.2. Diamond pyramid [SR-4, -24, -37, -49]

The Vickers indenter consists of a right diamond pyramid with a square base. The angle at the vertex, between opposite faces of the indenter (Fig.21) is 136 ± 0,5°. (Recommended tolerance for standard equipment : ± 0,2° or ± 0,1°). The corresponding angle between opposite edges of the pyramid is 148°7' ± 22' (± 9' for standards). All four faces of the indenter should be equally inclined to the axis of the indenter within 0,5° (0,3° in SR-37 and -49) and meet in a point, any line of junction between opposite faces being less than 0,002 mm in length (see Fig.21). For standard equipment max. 0,001 mm is desirable.

The indenter should be well polished over such a surface area that no unpolished part comes into contact with the material being tested when the indenter penetrates to a depth of 0,3 mm. (Penetration depth under a test load of 980,7 N in a soft material of 30 HV is approx. 0,25 mm).

Requirements concerning surface quality of the diamond and the indenter holder are similar to those for the Rockwell indenter. Some critical remarks on tolerances for the geometry of Vickers and Brinell indenters, together with the calculation of their effect on measured hardness were published by BARBATO in [B-4] .

6.3. Spherical indenter [SR-1, -8, -11, -12, -24, -37, -45, -50]

The Brinell, the Rockwell-B and -T indenter is a steel or hard metal ball. On account of different deformations during the test, hardness values obtained by using a steel or hard metal ball are significantly different for hardness above 350 HB.

The balls must be polished and free from surface defects. Spherical indenters may be mounted so that they can be interchanged (Fig. 22).

The ball diameter, when measured at not less than three positions, should not differ from the nominal diameter by more than the tolerance given in Table 7. These tolerances correspond to Grade 6 of ISO Recommendation R 286. Balls for ball bearings will normally satisfy this tolerance. The Vickers hardness of steel balls used for the Brinell test should be not less than 850 HV 10. This corresponds to the maximum diagonal values indicated in Table 7, where the correction for the curvature of spherical surface has already been taken into account.

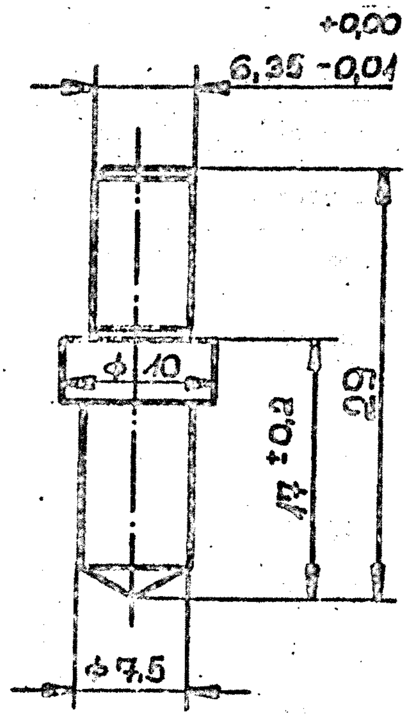
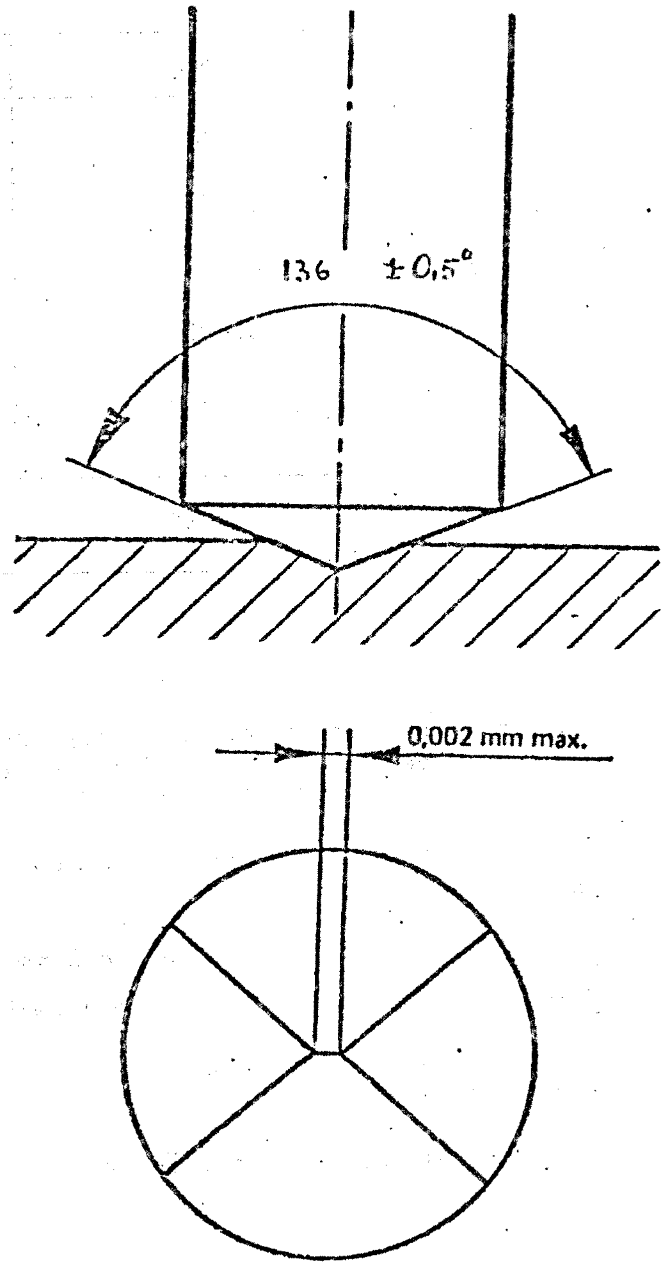


Fig. 20

Dimensions of Rockwell C indenter holder for a standardizing machine

Fig. 21

Specified geometry of a Vickers indenter



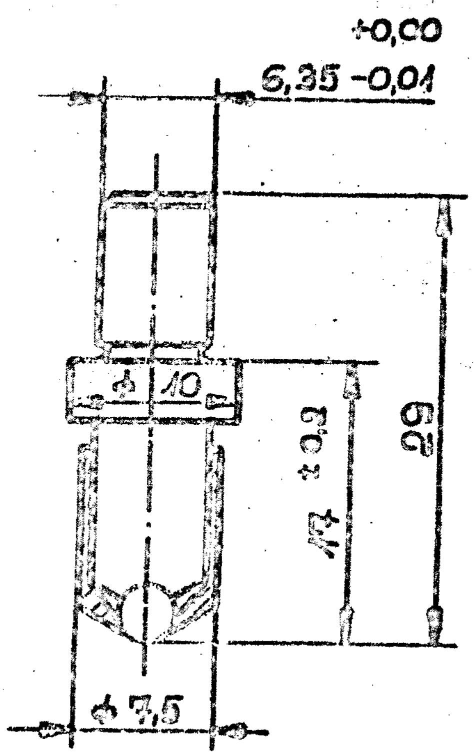


Fig. 22

Holder for spherical indenter

Ball diameter	Tolerance on diameter	Maximum value of mean diagonal of the indentation made with a Vickers indenter at 98,07 N
mm	mm	mm
10	± 0,0045	0,146
5	± 0,004	0,145
2,5	± 0,0035	0,143
2	± 0,0035	0,142
1	± 0,0035	0,139
1,5875 (1/16")	± 0,0035	0,141

For the purpose of verifying the size and hardness of steel balls used as indenters, it is sufficient to test a sample selected at random from a batch. The balls verified for hardness should of course be discarded.

For standard equipment reduced tolerances on the diameter are recommended [SR-37] :

± 0,002 mm for balls of 10 and 5 mm, and

± 0,001 mm for balls of 2,5 mm diameter or less.

The center of the ball and holder axis should be in line within 0,03 mm.

[SR-50] specifies a tolerance of ± 0,001 mm for all ball diameters.

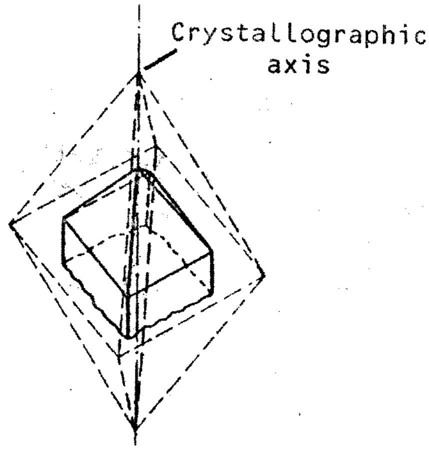


Fig. 23
Relative position of crystallographic axis and indenter axis

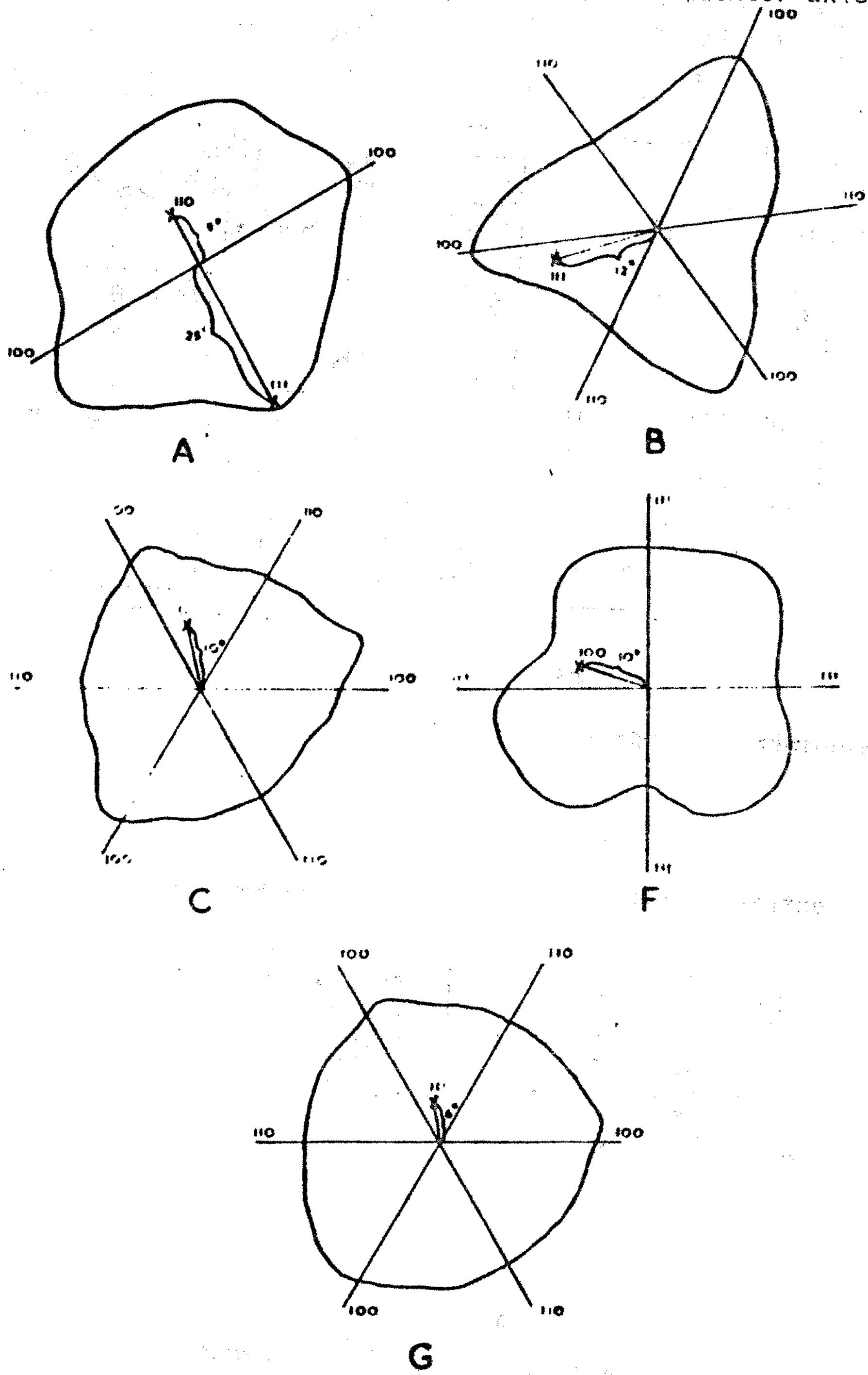


Fig. 24
Projection of the crystallographic axes of five indenters
on a plane perpendicular to the axis of the cone.

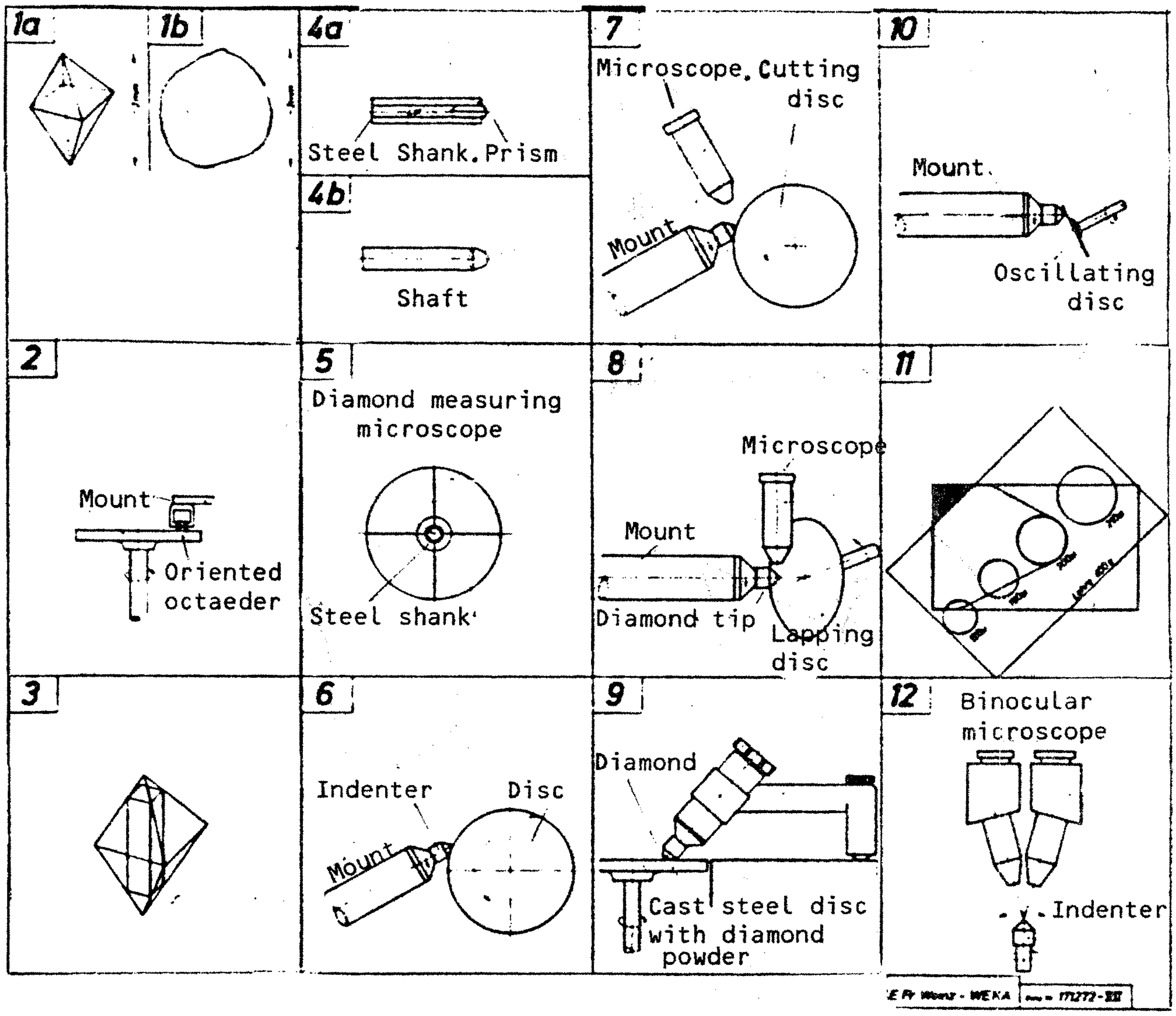


Fig. 25

Manufacturing operations of diamond indenters

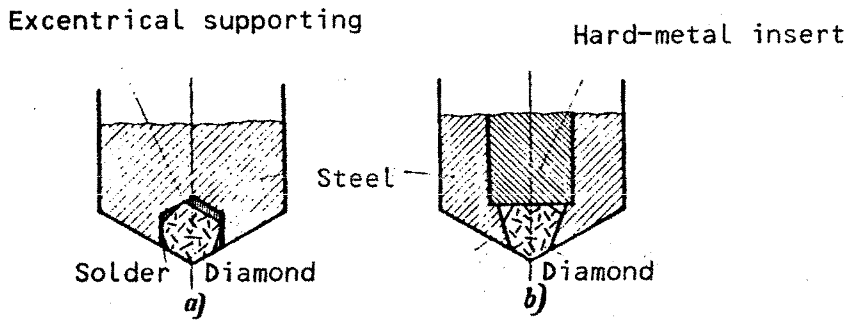


Fig. 26

Mounting the diamond tip of an indenter

7. Diamond as indenter material [F-2, G-4, N-1, W-13]

Diamond is the hardest among natural materials. It is pure carbon with cubic crystallographic structure. Its well-known resistance to wear makes it an ideal cutting tool material. This, combined with an extremely high compression strength and a low coefficient of friction in contact with most materials predestine its use as a material for hardness testing indenters. But diamond is anisotropic. Cutting directions and rate of cutting vary appreciably according to the plane relative to the crystallographic axes (Fig. 23). The plane faces of a Vickers pyramid indenter can be produced much more easily than the conical and spherical surfaces of a Rockwell indenter. When generating a cone, the change of cutting rate with change of plane produces the lobing which may have two, three or four-fold symmetry according to whether the (110), (111) or (100) axis of the crystal is closest to the axis of rotation. Fig. 24 shows the projection of the crystallographic axes of five indenters on a plane perpendicular to the axis of the cone, together with the measured out-of-roundness of the cone [M-1]. The diagrams were prepared on the basis of X-ray photographs. The projection of the axis nearest to the cone axis is denoted by X.

The art of the diamond cutter consists of finding the preferential planes along which cutting is easy and can be executed correctly, further the wear resistance of the ready made indenter is considerably higher.

7.1. Production of diamond indenters [F-2, W-14, W-15]

The requirements for diamonds as indenter are higher than for diamonds for general industrial applications. The production process of Rockwell indenters can be followed on Fig. 25, according to WEINZ. The raw diamond can be an octaeder with recognizable structure (1 a), and this is more expensive than a raw diamond with undiscernible orientation (1 b). For high quality indenters raw diamonds according to 1 a are always used, of which correctly oriented four-sided prisms having a diameter of at least 1,7 mm (3) are ground on a rotating disc impregnated with diamond powder (2). The raw diamond is clamped in such a way that the plane of cutting should not be perpendicular to the main crystal axis. Raw diamonds of the shape 1 b with a structure between a dodecahedron and a sphere, cannot be oriented, consequently up to 20% of indenters made of them break during use.

Colour of the raw diamond is of secondary importance, nevertheless green or yellow shadings are preferred, while dark brown ones are undesirable, as these may be too soft on account of inclusions.

The effect of correct alignment of cutting planes was examined at the National Physical Laboratory [N-1] by employing Laue back reflection X-ray techniques. The symmetry of form is critically dependent upon alignment, an error greater than 5° promotes a degree of lobing which excludes the possibility of the spherical tip having radii for all azimuths being within tolerances of standard specifications.

The next operation of the process shown in Fig. 25 is soldering the diamond prism into the bore of a steel shank (4 a) or to the end of a shaft in the case of not oriented raw material (4 b). Silver-copper soldering, with prealable metalling with titanium is executed in vacuum of 7.10^{-3} Pa (5.10^{-5} Torr) at a temperature of 860 °C, since diamond would burn above 800 °C in the presence of oxygene. This technique ensures a perfect fixation of the diamond in the shank, no relative displacement being possible even under high test loads.

The classical designs of mounting the diamond tip are shown in Fig.26 [W-13] . Solution b) is preferable because the diamond is supported on a larger surface by a hard-metal insert, ensuring secure positioning. In case a) the diamond is supported only at one point, which may be excentrical to the line of action of the load. In the case of a not perfect soldering the elastic or permanent displacements of the diamond tip may introduce unacceptable measurement errors [K-6] .

The following operation in the production technology according to Fig. 25 is centering the diamond axis on a microscope by rotating its table (5). Hereafter the diamond and the shank are ground by a very rough disc to a cone of 110 ° (6) so that the steel of the shank should not come in contact with the diamond cutting disc during the next operation of preparing the 120° cone (7). Fig. 27 shows the indenter tip with the conic sections of 110° and 120°. To ensure a correct blending of the conical and spherical surfaces, the cone is lapped with fine grain diamond powder prior to cutting the radius (8). Cutting and lapping operations are observed on a microscope. Vickers indenters are cut of course without rotating the shaft (9) on a cast steel disc covered with diamond powder. The correct alignment of the facet with respect to the crystal axis requires special knowledge.

The spherical part of the Rockwell indenter is produced by grinding and subsequent lapping, by realizing a composed relative motion of indenter and lapping disc covered with diamond powder of possibly uniform grain size. The Rockwell indenter consists of rotation surfaces, what is contrary to the crystal structure of the diamond. The difficulty met during manufacture is that the cutting machine cannot be built so stiff that cutting rates in various directions of the indenter be identical. The mount itself may come into oscillation as hard and soft regions of the diamond are contacted alternately. Grinding discs without loose diamond powder on it produce a cone shape better approximating circularity, but surface quality is not so good. Diamond powder soaked tools produce cones and spherical parts deviating more from the ideal, while surface quality is better. From the aspect of hardness measurement, both true shape and surface quality are important, the two requirements should be met by a reasonable compromise.

At the NPL it was considered necessary to preform a multi-sided pyramid [N-1], prior to cutting the cone, to allow for the appreciable differences in cutting rate. Initially a symmetrical pyramid with sixteen facets was formed with excess material in the softer regions and it was subsequently rotated to remove excess material at the intersections of the facets. During rotation, in order to attach left and right cutting directions equally, it was necessary to alternate between these two cutting directions and this partially counteracted the effect of the faster cutting rate in the soft directions. With careful selection and control of cutting directions, it was necessary to leave excess material of only 1 or 2 μm on the soft facets of the pyramid. This small amount of material was removed during rotation and the resulting uniform cone was circular in cross section to the order of ± 1 μm variation in radius. It is necessary for the indenter to be rigidly mounted, to discourage the formation of lobing during the rotation stage, but allowance must be made for expansion of the mount due to the heat generated when cutting the diamond. The design adopted gives the indenter a reciprocal motion parallel to the disc radius in order to distribute the wear over the annular area of the disc surface and to obtain a monodirectional cutting action. With this apparatus it was relatively simple to produce a cone with an included angle of 120° well within the tolerance of ± 6 minutes of arc. The spherical tip is also susceptible to lobing in the final stage

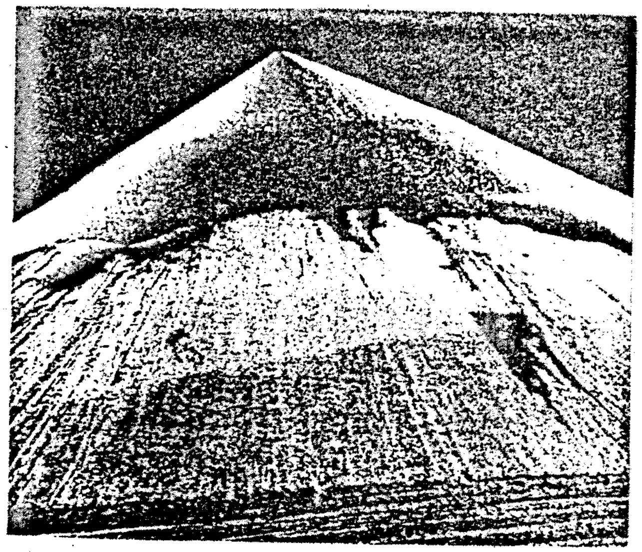
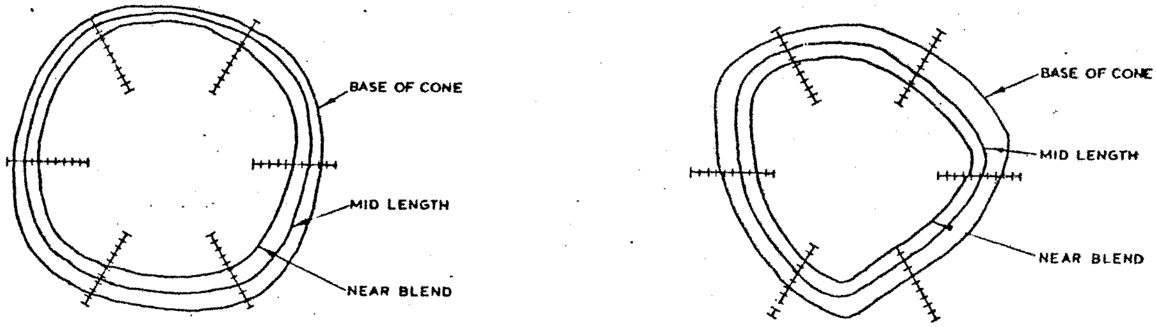
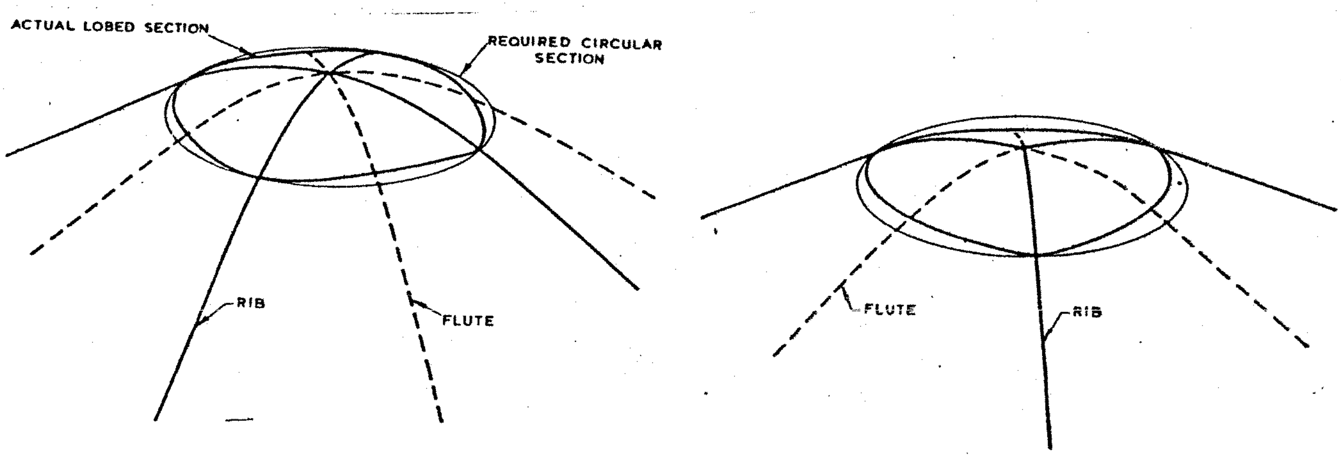


Fig. 27
Tip of a 120° cone indenter undercut to 110°.

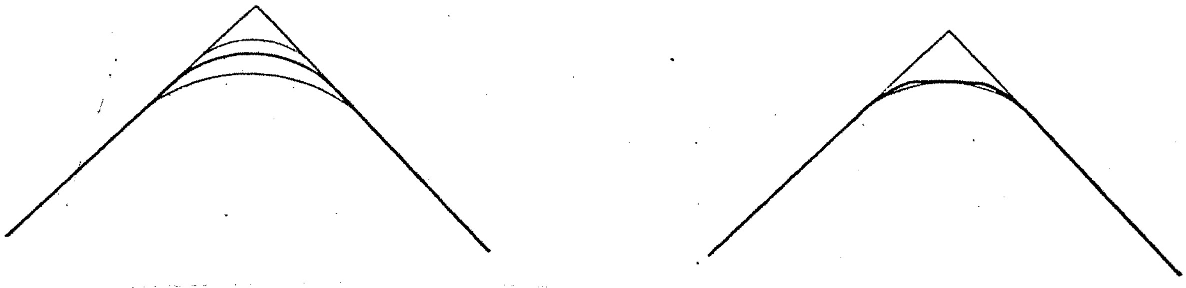


a) Fig. 28 b)
Talyrond records of four and three-lobed cone indenters



a) Fig. 29 b)

Two types of cone to sphere transition



a) Fig. 30 b)

Blending of cone and sphere

a) Correct b) Having an annulus of excess diamond

Fig. 31

Ideal polish

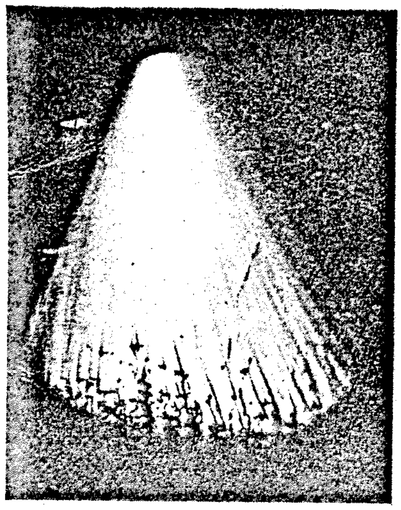


Fig. 32

Good polish with visible scars of cutting

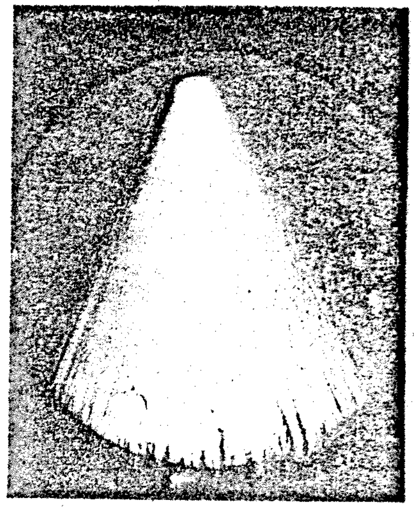


Fig. 33

Good polish with visible grooves and pits

Fig. 34

Grinding grooves and flaws

Fig. 35

Circular cutting grooves

Fig. 36

Porous structure of the diamond and grooves

(For better quality pictures see the original [M-20] .)

of the production of the indenter, if purely rotational methods of forming are used. Therefore a preforming of the tip is envisaged, prior to rotation, although difficulties may be encountered in the control of the facets which will be very small indeed.

Checking the dimensions is carried out after each operation (11 on Fig. 25) by a 400 x magnification. The last operation of the production process is a macroscopic surface checking (12). A mirror-like surface structure is a requirement along the part of the indenter tip that may be in contact with the specimen.

7.2. Shape errors of the diamond indenter

MARRINER and WOOD [M-8] grouped defects affecting the performance of Rockwell C indenters as follows :

Included angle error
Average radius error and type of blending
Magnitude and type of lobing
Position of radius with respect to the apex of the cone
Local variations at the extreme tip.

The effects of included angle and radius errors on the measured hardness value were discussed in details in the OIML Publication Factors Influencing Hardness Measurement.

The relationship between the number of lobes and the alignment of the indenter was already mentioned in connection with Fig. 24. Talyround records of four and three-lobed indenters are shown on Fig. 28. It will be seen that not only do the lobes and minor characteristics remain in position as the sections progress from base to tip of the cone, but the magnitude of the out-of-roundness does not appreciably diminish. A consequence of the uniformity of the out-of-roundness is that the included angle of the cone remains constant regardless of whether measurements are made in sections through ribs or flutes of the cone.

The persistence of the ribs and flutes of the lobed cone into and beyond the blend with the spherical tip was found to be a characteristic of indenters examined at the NPL and in consequence the tip was not truly part of a sphere. Fig. 29 illustrates the basic form of two frequently occurring types of indenter, but variations from these forms occur when the crystallographic axes are mis-aligned or other defects are present. It will be seen from Fig. 29 a that the radius of the tip must be different for an axial section through the ribs from that of an axial section through the flutes. Calculation shows that if four-lobed indenters of this type have an out-of-roundness of the cone of more than 0,003 mm on radius then the radius of the tip will vary by more than 0,205 to 0,195 mm. Projection at 500 times easily reveals that this is true. Projection of the axial sections of three-lobed indenters, Fig. 29 b, reveal greater uniformity but it is difficult to assess the radius as the profiles are asymmetric and never fit true circular arcs.

A common defect of indenters, and one that is very difficult to measure, is that the spherical tip is incorrectly positioned with respect to the apex of the cone. Fig. 30 illustrates schematically the profile of an indenter with a correct radius together with the profiles of large and small radiused indenters with perfect blending. In practice, indenters with radius errors alone as illustrated in Fig. 30 a rarely occur, and the defect of incorrect positioning often appears as a large or small radius for the major part of the spherical tip which is blended into the cone by changes of curvature. Fig. 30 b illustrates the large radiused type, which is characterised by an annulus of excess diamond at the position where the curvature changes, and may be regarded as a large radiused indenter in which the spherical tip is too near the apex. Such indenters can be made to function correctly at one, or sometimes two levels of hardness but, unless additional defects are present, give incorrect values at other levels of hardness.

A defect which is characteristic of particular manufacturers, and may in fact be used by them to adjust the performance of an indenter at the hard end of the scale, is local excess or, alternatively, slight flattening at the extreme tip of the radius.

The main cause of differences in the performance of indenters lies in imperfections in the geometric form. Except for a precise and quick means of determining the position of the spherical tip with respect to the apex of the cone, the means are available to measure the departures from nominal form and patient work will determine their quantitative effect. However, it has never been good economics to use sophisticated measuring merely to reject a product and there is need for a cutting and polishing technique which will produce indenters free from geometric defects.

7.3. Surface deficiencies

There is a large variety of surface deficiencies on diamond indenters, the decision on their acceptance or rejection is greatly influenced by subjective judgment. Specifications are vaguely formulated such as 'should be clean, free from cracks and surfaces' or a 'surface without cracks, pits or other flaws'. Aids to visual inspection, such as charts with photographs summarizing prior experience are very helpful.

Based on the experience of testing several thousand indenters, MIKOSZEWSKI [M-20] published a series of typical surface deficiencies. Surface defects can be classified into two wide groups : those resulting of the manufacturing process which consequently occur on new indenters, and those resulting from the use of the indenter, which is not necessarily the consequence of faulty use, it may be also the result of normal wear.

The following series of photos demonstrates the first group. Fig.31 shows a diamond indenter with an ideal polish both on the conical and the spherical surface. On Fig. 32 the polishing is good, but scars of cutting are visible on the conical part in the form of grooves in the direction of the generatrix. On the indenter shown on Fig. 33 some pits are also visible. On Fig. 34 grinding grooves are apparent, together with a certain amount of flaws. Nevertheless this indenter is still regarded as acceptable if other parameters meet the specifications.

The judgement of surfaces shown on Figures 35 and 36, however, is disputed, though such deficiencies occur frequently. On Fig. 35 circular grooves resulting from cutting are visible. In Fig. 36 the porous structure of the diamond with superimposed grooves is visible.

Fig. 37
Rough surface with pores and cracks

Fig. 38
Porous and rough surface

Fig. 39
A pit on the spherical part, grooves on the cone

Fig. 40
Heavy scratch on the conical part

Fig. 41
Heavy crack in the axial direction

Fig. 42
Fault of the spherical tip

(For better quality pictures, see the original [M-20].)

Fig. 43
Vickers indenter of
good quality diamond

Fig. 44
Crack from the surface
towards the interior. Broken edge.

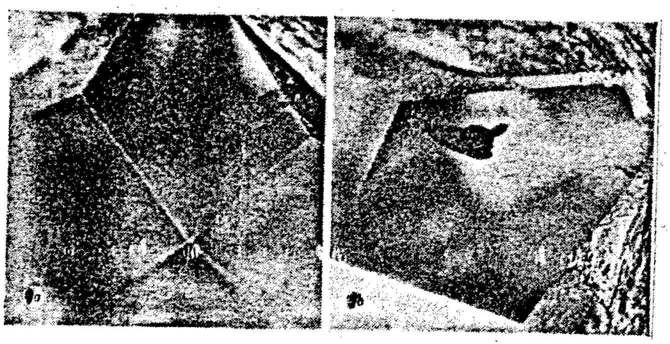


Fig. 45
Reground diamond with large crack.

Fig. 46
Diamond with
big inclusion

Fig. 47
Concentric agglomeration of
small inclusions

Fig. 48
Big pore, and cracks along two pyramid surfaces

(For better quality pictures, see the original [K-3].)

The next two photographs show completely unusable diamond indenters. On Fig. 37 rough surface parts with pores and cracks are apparent. The indenter shown on Fig. 38 has porous and rough surface both on the spherical and conical part of the indenter, necessitating a rejection. When examining defects belonging to the second group, it should be emphasized that the source of such deficiencies is frequently to be found in defects of the first group. Experience shows that indenters with raw surface or with grooves are exposed to a more rapid wear in normal usage.

The Rockwell indenter shown on Fig. 39 has a pit on the spherical part and grooves on the cone. On Fig. 40 a heavy scratch can be identified on the conical part. A defect of this kind may soon lead to the break of the diamond, therefore it should be discharged as soon as the defect is observed. In some cases, if the dimensions of the diamond insert permit it, the indenter tip can be mounted and ground anew, though some authors [F-2] reject the method of regrinding in principle.

In Figures 39 and 40 heavy reflections and refractions of the light make an objective judgement even more difficult. On Fig. 41 refraction of the light is coupled with a heavy crack in the axial direction of the diamond structure together with some scratches. This completely unusable indenter is shown only to present a bad example. The crack resulted also in a break of the spherical tip, what could have been avoided by a regular visual checking of the indenter, eliminating or regrinding it at the appearance of the first scratch. A typical fault of the spherical tip is shown on Fig. 42, what was the result of incorrect testing practice.

The defects inside and on the surface of diamond indenters are classified by KERSTEN [K-3] as follows :

- cracks in the diamond,
- superficial cracks of the diamond,
- cracks connected with inclusions,
- small inclusions, occurring separately,
- small inclusions in concentric agglomeration,
- big inclusions.

In the case of Vickers indenters cracks and inclusions can be recognized and observed without difficulty, even in mounted diamond, if it is colourless or of a light colour. The microscope can be focused to different depths, thus the whole diamond tip can be checked, the distance of flaws from the surface determined. The cone surface of Rockwell indenters, however, is reflecting light beams so strongly that a transillumination of the whole diamond is difficult. Thus recognition of cracks and inclusions under the surface is not always possible. Superficial pores and cracks may be the sign of the existence of many small inclusions under the surface, similar to that shown on Fig. 47.

The illustrations show some typical defects of Vickers indenters. On Fig. 43, an indenter made of good quality diamond is shown. The flaw being beyond the active part of one of the pyramid surfaces is the result of careless handling but has no influence on measurements. On Fig. 44 a crack from the surface towards the interior of the diamond can be seen, coupled with a break of the pyramid edge. This diamond is not suited even for regrinding. The small dark points are separately occurring small inclusions lying so deep that they do not affect functioning. Fig. 45 shows a reground diamond with a large crack which is not easily recognizable (45 a), with several superficial cracks and with a big inclusion (45 b). On account of the large crack and of the inclusion this indenter should be sorted out. On Fig. 46 a diamond with a big inclusion can be seen. The bright places on the picture are the boundary surfaces of the inclusion or already existing cracks. This indenter is not suited either for use or for regrinding. The diamond shown in Fig. 47 has a concentric agglomeration of small inclusions (47 a). By adjusting illumination it can be seen that these inclusions reach to the surface of the pyramid, resulting in the formation of pores (47 b). The use of this indenter is impossible on account of the porous surface. Fig. 48 shows an indenter with a big pore, connected with cracks along two pyramid surfaces (48 a and 48 c), and with a big inclusion in the diamond, under the tip of the pyramid. After having performed 10 indentations with this diamond, cracks originatinating from the big inclusion (48 b) appeared.

8. Methods and equipment for testing indenters

The equipment for determining indenter characteristics, especially radius, angle, straightness and surface quality, is to be discussed in the following. The aim of this chapter is to present and summarize published data on equipment developed specially for purposes of verification laboratories of hardness testing machines. For basic knowledge on optical instruments, on principles of measurement, etc. the relevant literature should be consulted.

Indenter testing equipment can be classified according to the geometrical parameter being measured (measurement of angle, radius, etc.) or according to the working principle of the apparatus. For the sake of convenience the last mentioned classification was employed here. So we discuss projection methods, measuring microscopes, interference methods, and finally miscellaneous special methods. In each case uncertainty characteristics are underlined, if available.

8.1. Testing indenter geometry by projection

Projection methods are used especially for determining the radius of Rockwell C diamond indenters. The principle is shown in Fig. 49. The system consisting of an objective and an ocular, functions as a microscope.

To determine the necessary magnification of the projected image it should be taken into consideration that the radius of 0,2 ± 0,01 mm corresponds to 40 ± 2 mm and to 200 ± 10 mm at magnifications of 200 x and 1000 x , respectively. A tolerance band of ± 2 mm on the screen is not very convenient in testing practice, especially if we want to partition it into smaller bands, e.g. corresponding to steps of 2 µm, what is a reasonable requirement. For the sake of convenience the master circle arcs drawn on the projection screen should include only a central angle of 60°, corresponding to the spherical part of the HRC-indenter.

HILD [H-4] gave an optimum uncertainty of ± 0,003 mm, by using an objective of 3 x and an ocular of 12 x magnification. The accuracy of the master radii on the screen can be checked by projecting the image of a ball of known diameter.

At determining angles of the Rockwell indenter by the help of a projector, relatively high uncertainties were found and, what is more important, systematic errors with respect to angle values determined on a microscope, going up to 20' or more, were found. Projection can be employed for determining the angle between the opposite edges of Vickers indenters [W-13] , supposed that the screen is exactly parallel with the plane formed by the two edges of the indenter.

The checking of the master radii on the projection screen by the help of a steel ball having a radius of 0,202 mm is shown in Fig. 50. YAMASHIRO and UEMURA [Y-9] also give a value of ± 0,003 mm for characterizing the error of projection (at 200 x magnification), but only for the steel ball which can be regarded as perfectly spherical, in contrast to the indenter which may have different radii in different cross sections. Different observers may assign different radii to the indenter image, therefore in practical indenter evaluations the uncertainty is higher.

The projection equipment employed by LUCZYWEK [L-5] is shown in Fig.51. Magnification ratio is 250 x or 500 x. The screen carries master arcs corresponding to radii of 0,18, 0,19, 0,20, 0,21 and 0,22 mm. The screen can be rotated in its plane so as to facilitate the finding of the arc corresponding to the image of the indenter.

TOLMON and WOOD [T-1] found that at least a 200 x magnification is necessary to determine satisfactorily whether the point of the Rockwell diamond indenter conformed to requirements when projected. For the purposes of a thorough investigation the magnification was increased to 1000 x , by the use of a projection lens system in which a one-inch objective was used in combination with a 12 x eyepiece. Slightly convergent light, using a 500-watt mercury-vapour lamp as source, was found to improve the contrast on the shadowgraph without distortion. Although both contrast and definition were inferior to that obtainable at lower magnifications, these disadvantages were more than offset by the large tolerance band, 10 mm wide, made available, and it was possible, by reference to a 1000 x master drawing, to estimate the departure of the profile from nominal to an accuracy of 1 mm at the image on the screen, namely to 0.001 mm on the penetrator point itself. At this magnification the radiused point and flank could be readily checked for smooth blending. By rotating the penetrator both contour and blending could be examined in various axial planes.

A projector for magnifications from 20 x to 500 x is shown in the paper of WEINZ [W-15] together with an apparatus designed by MEYER serving for the accurate angular positioning of the indenter during the test. A similar apparatus can be found in a publication by PILIPTCHUK and STEPANOW [P-15]. The projector used by these authors has a 300 x magnification.

YANO et al. [Y-12] organized an experiment to find the best method of assigning the correct master drawing radius to the image of the indenter. With the first method the degree of correspondance of the image and of the arcs was expressed by a grade value. With the second method the optimum corresponding arc was selected. In the third method the radii in the drawing were changed from large to small, and then from small to large and the best fitting arc was chosen. Best results were obtained with the last mentioned method (the 2 standard deviation value was about 1% of the nominal radius). The optimum correspondance method was somewhat more uncertain, while the first method (grades) had an uncertainty which was about four times higher than that of the third method. These values apply for a magnification of 1000 x . By decreasing the magnification to 100 x, uncertainty values were doubled.

Recommendation [SR-37] gives a 300 x magnification as minimum requirement.

8.2. Use of measuring microscopes

The included angle of the cone of Rockwell C indenters, and the angle between opposite faces or edges of Vickers indenters is most frequently measured by a measuring microscope with goniometer eyepiece. The line of the goniometer is adjusted to the cone or pyramid image in such a way that a narrow light slit remains between them. Difficulties may arise if the generatrix of the cone is not straight. In this case a mea-

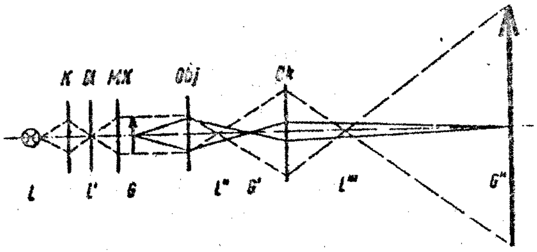


Fig. 49

Schematic drawing of a projection equipment for indenters. (Light source L, condenser K, microcondenser MK, objective Obj, ocular Ok, diaphragm Bl, tested indenter G)

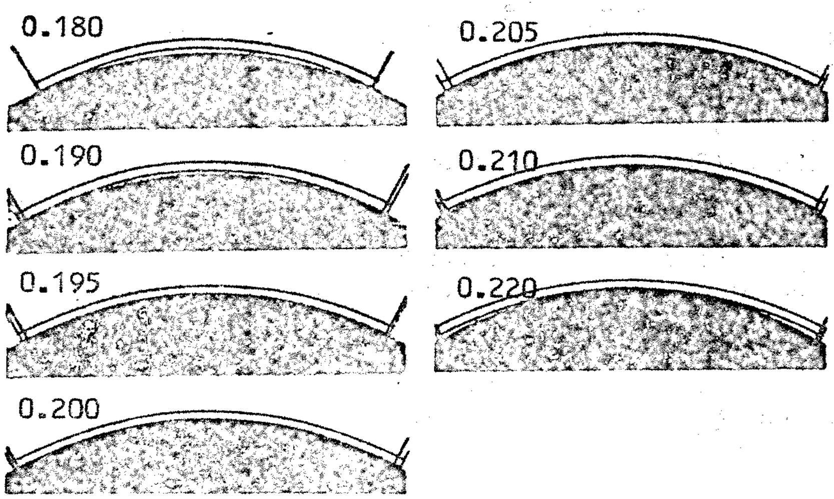


Fig. 50. Checking the master screen for radius projection by a steel ball of R 0,202 mm.

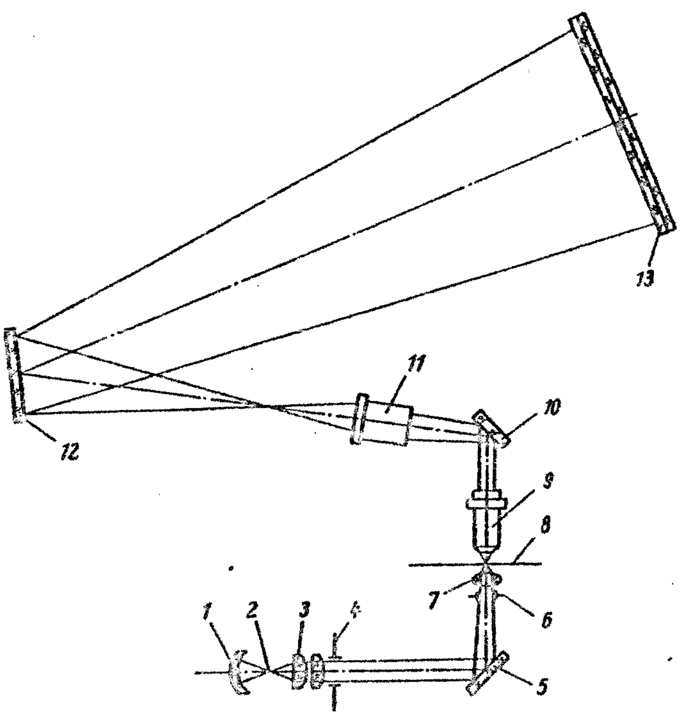


Fig. 51. Projection equipment for measuring the radius of a Rockwell indenter.
(1 concave mirror, 2 light source - halogene lamp 100 W, 3 collector, 4 and 6 diaphragms, 5, 10 & 12 mirrors, 7 condenser, 8 object table, 9 objective (5 x or 10 x), 11 ocular (15 x), 13 screen).

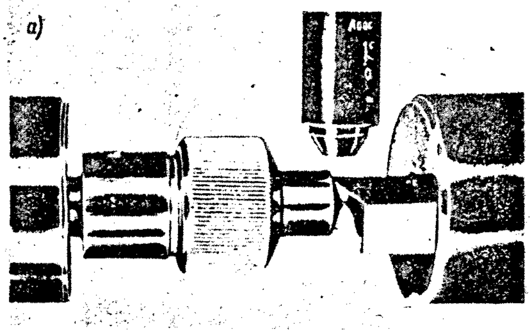
surement near to the point of blending with the spherical part is recommended. HILD [H-4] employed a 100 x magnification, whereby the uncertainty of the mean value was found to be ± 4'. PILIPTCHUK [P-15] used a microscope with 120 x magnification. In Recommendation [SR-37] a 50 x magnification and a maximum error of angle measurement of ± 3' is specified for standard indenters, with measurements in four positions. For indenters of general usage OIML International Recommendation N°36 [SR-24] specifies an uncertainty of ± 6', both for conical and pyramid indenters. MEYER (cited in J-1) specified ± 5' as the maximum error for cone angle measurements on a microscope, and ± 0,005 mm as the uncertainty of radius determination. LUCZYWEK [L-5] also indicates an uncertainty of angle determination by the goniometer eyepiece of about ± 5'.

For measuring the angle between faces of pyramid indenters the use of the STOE goniometer is recommended in [W-15]. YAMAMOTO [Y-7] developed a special microscope by which the angle between the normals to the faces of a Vickers indenter is measured.

MIKOSZEWSKI and BOLESLAWSKA [M-19] developed an accessory to measuring microscopes which allows the measurement of the angle between cone axis and holder axis of Rockwell indenters (Fig.52). The indenter is clamped in the microscope similarly as in a hardness tester, with holder axis perpendicular to the objective axis. A polished surface perpendicular to the holder axis is contacted with the point of the indenter. In this case both the image of the indenter point and its mirror image on the polished surface can be seen in the microscope as shown in Fig. 52 b. By measuring angles ε_1 and ε_2 , the angle γ formed by the holder axis and the cone axis can be found as

$$\gamma = \frac{\varepsilon_1 - \varepsilon_2}{4}$$

The uncertainty of determining γ is given as ± 5'.



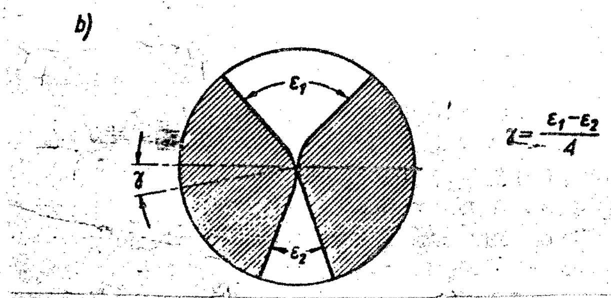


Fig. 52.

Microscope accessory for measuring the angle between cone axis and holder axis.

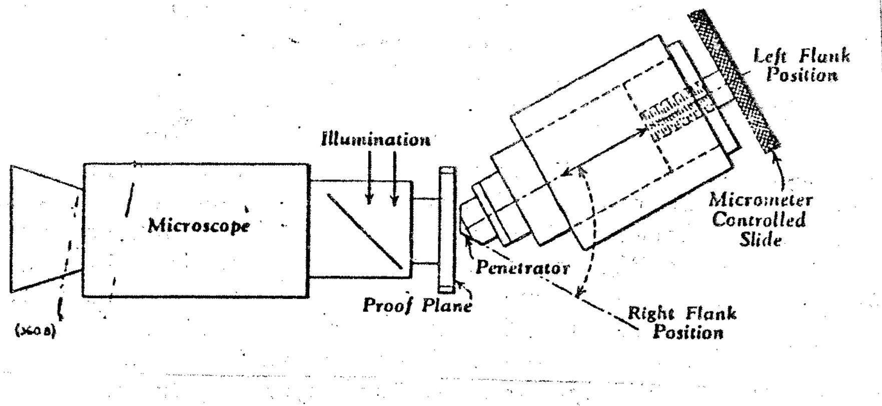


Fig. 53. Apparatus for cone angle measurement by interference alignment.

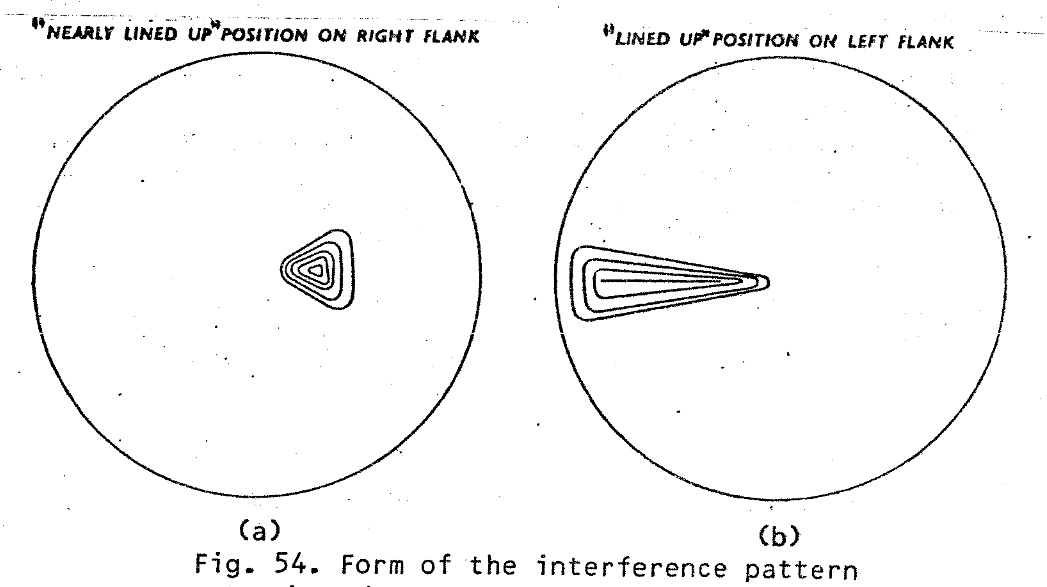


Fig. 54. Form of the interference pattern at using the apparatus shown in Fig. 53.

8.3. Light interference methods

Interferograms obtained on a light interference microscope are, in effect, contour maps having a contour interval, i.e. the spacing between consecutive fringes, of about 0,25 µm. Interference methods are suitable to check the straightness of the flank (generatrix) of the cone indenter, further the correct blending of cone and sphere, the shape of the spherical part of the indenter, or to align the cone for angle measurements.

TOLMON, WOOD and HALL [T-1, T-2, T-3] used the interferograms of the generatrix with the aim of determining cone angle (Fig. 53). The penetrator was mounted on an accurately divided rotary table with the axis of the cone horizontal and its point close to the axis of rotation of the table. The penetrator could be moved axially by means of an accurate slide controlled by a micrometer screw. The cone angle was measured in a horizontal plane by setting each flank in turn parallel with a datum plane formed by the semi-reflecting proof plane of an interference microscope of magnification x 50 mounted with its axis horizontal. By bringing the penetrator flank close to the proof plane and illuminating it with white light, a coloured interference pattern was obtained; this pattern is illustrated in Fig. 54 (a), in which the lines represent successive spectra.

The form of the pattern was found to be extremely sensitive to any out-of-parallelism between the flank and proof plane, an angular movement of 1 minute of arc being readily observable providing the flank was sufficiently straight. The interference pattern with the flank set parallel to the plane is shown in Fig. 54 (b). It is characterised by a central straight band which, in this condition, has reached a maximum length. Over the greater part of its length, this central band appears as one colour, graduating to the next spectral colour at each end in such a way as to provide a symmetrical appearance. This symmetry of colour was of considerable assistance in obtaining the correct setting, and was responsible for the choice of white light in preference to the more commonly used monochromatic light for work of this type.

Rotation of the indenter about its axis enables measurements to be made in many azimuths.

The accuracy with which the cone angle can be determined depends principally on the length and straightness of the flanks. In the case of an indenter having a long flank of about 1 mm, which was straight within 0,25 µm, an accuracy within ± 0,25 minute of arc can be attained for the mean cone angle. For shorter straight flanks accuracy values of ± 1 minute of arc were found.

The apparatus used by NASH [N-3] was an extension of the equipment shown in Fig. 53. Suitable adjustment was provided to move the indenter in various coordinate directions. The location of the rotary table was improved so as to have a sufficient accuracy. The position of the microscope was monitored by a transducer.

The modified equipment permits to assess the position of the radius with respect to the conical flanks, i.e. indenter errors shown in Fig.55. In the upper part of the figure the correct radius is too far back, the blend is undefined. In the lower figure the correct radius is offset, the blend shows a sharp edge at one side. The proposed measuring and

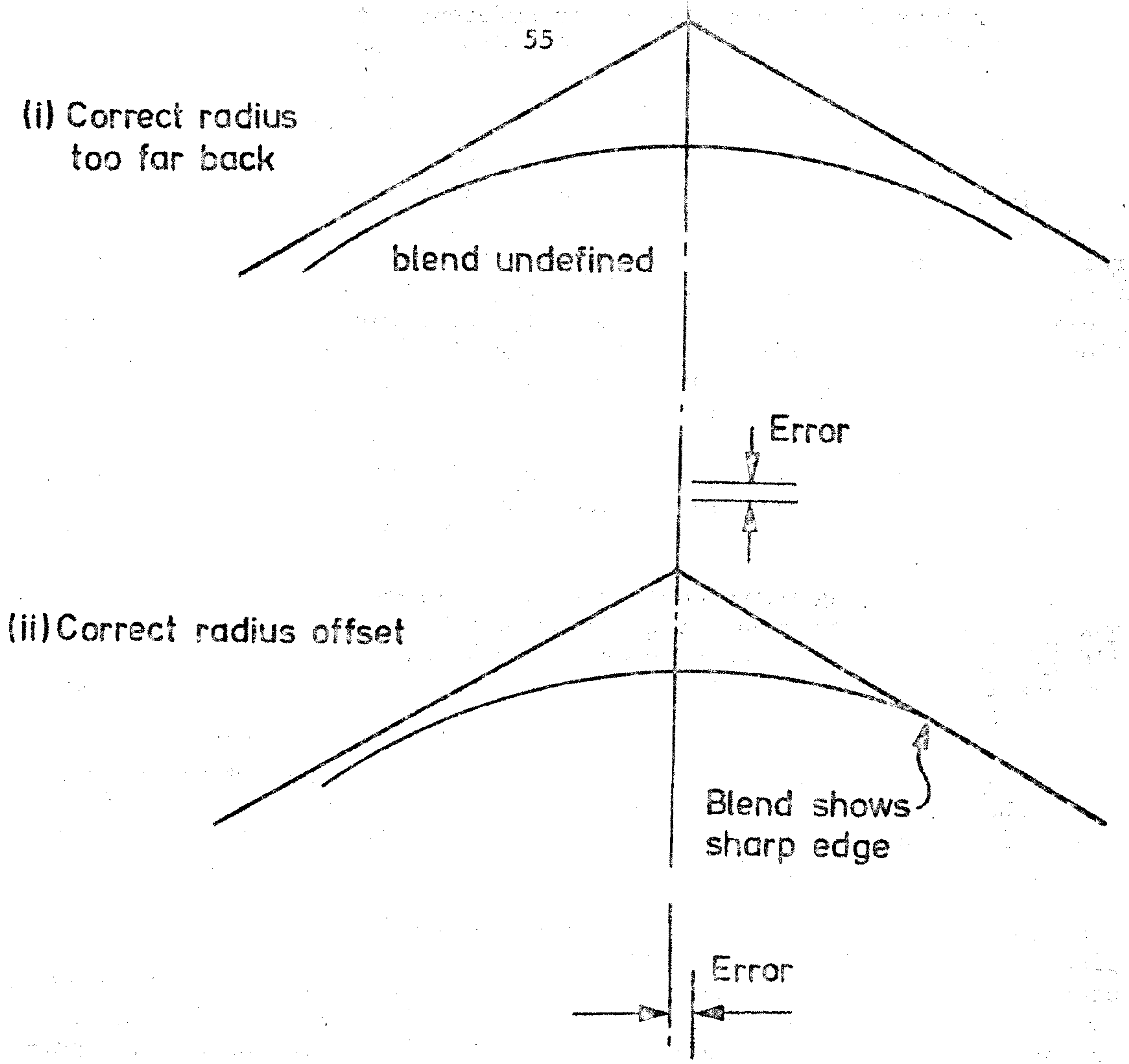


Fig. 55. Two types of error of form

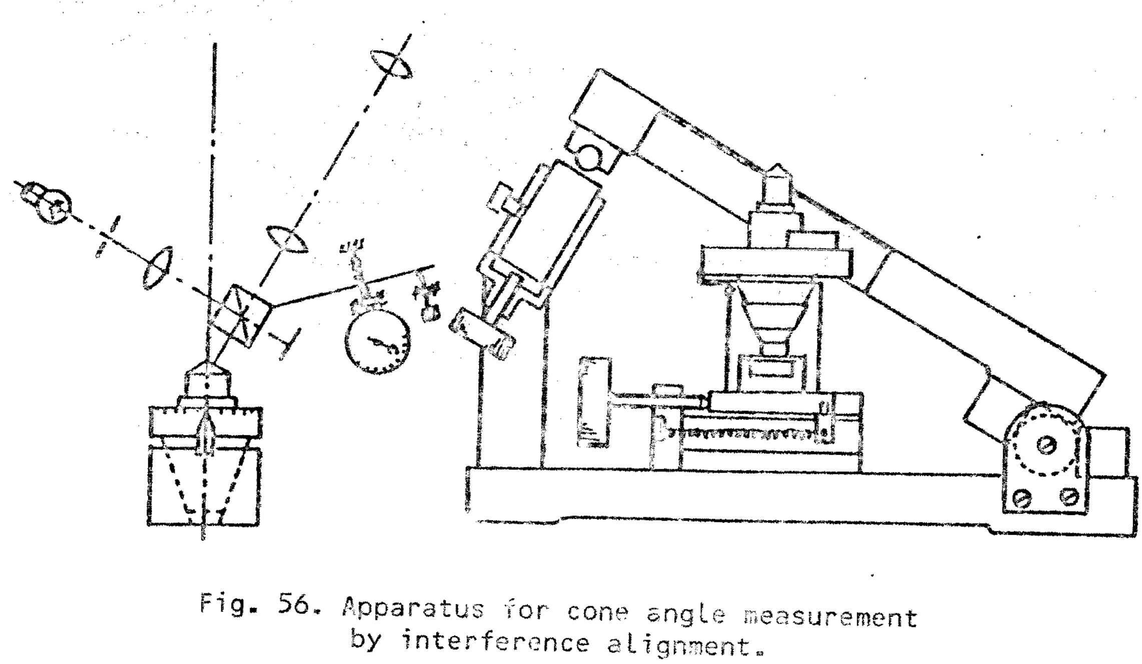


Fig. 56. Apparatus for cone angle measurement
by interference alignment.

calculation method allows to detect errors of this kind, by fitting circles over less than the complete circumference of the tip. A detailed measurement of departures from a fitted radius is possible.

YAMASHIRO and UEMURA employed the same principle of angle measurement by using the apparatus shown in [Y-9] .

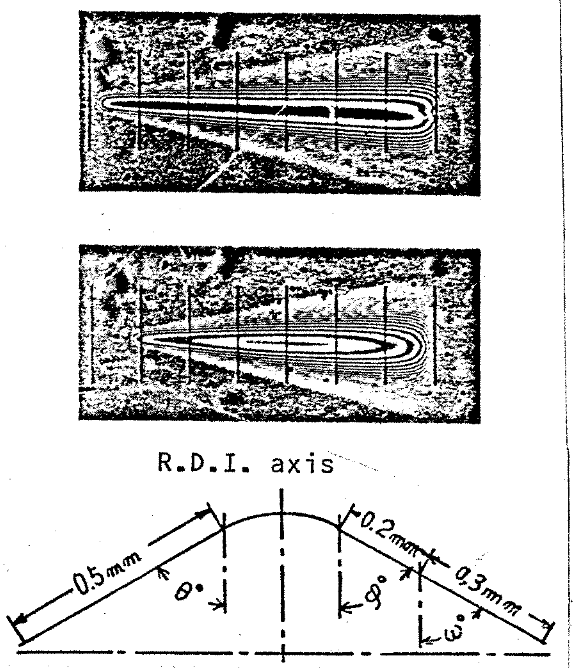
A similar apparatus used by YANO, ISHIDA and KAMOSHITA [Y-12] is shown in Fig. 56. The interference pattern of a diamond cone having a generatrix straight at a length of 0,5 mm is shown in Fig. 57 (a). This indenter is suited for use in a standard equipment. Fig. 57 (b) shows the pattern of a Rockwell C indenter which is suited only for common, industrial applications because the straight section of the flank is only 0,2 or 0,3 mm long. The cone angle of such indenters is determined separately for two sections (Fig. 57 (c)) .

The accuracy of cone angle determination by the help of the micro-interferometer is characterized by the standard deviation value of 0,5' [Y-8] .

Another measuring microscope using interference for adjusting indenter flanks for angle measurement (magnification 200 x) was described by VAŠÁK [V-1] . At repeated measurements of the same Rockwell or Vickers indenters the standard deviation of angle determination was found to be 0,4' to 0,8'.

The blending of the radius with the flank of Rockwell C indenters, i.e. whether the spherical and conical surfaces are truly tangential, can be appreciated during the projection of the indenter or during the measurement of the cone angle. A considerable improvement can be realized, however, by the help of interferograms and photographs of blendings obtained on a microinterferometer at a 350 x magnification [T-2, T-3] . Typical indenter blendings are shown in the interferograms on Fig. 58, reproduced half-size from the originals at 1000 x magnification. Fig. 58 (a) shows an almost perfect blending, whilst (b) and (c) show lower degrees of blending. These interferograms were made with the microscope axis perpendicular to the generatrix of the cone.

Interferograms of the spherical point of the Rockwell C indenter can be prepared if the microscope and the indenter are arranged coaxially. Typical interferograms published by JUNGE and MÜLLER [J-1] are shown in Fig. 59. Photographs taken on an interference microscope give a very clear general impression of the shape and surface of the tip of the penetrator, though only over a restricted distance corresponding to an axial depth of about 0,005 mm from the apex of the penetrator [T-1] . The Zeiss-Linnik-type interference microscope used for this purpose is adapted for use with mercury green illumination. Newton's rings are formed between the spherical point and an optical flat, at a magnification of 600 x. The interference fringes, the contour maps of the point of penetrator are formed in planes at successive axial distances from the apex of half wavelengths of mercury-green light, i.e. at intervals of 0,25 µm. The interferograms of Fig. 59 show some penetrators which are out of round and have surface blemishes. The microinterferogram may reveal lobing or surface blemishes which were undetected by any other technique.



(a)

(b)

(c)

Fig. 57. Interference patterns of indenters having a generatrix straight over 0,5 mm (a) and over 0,2 mm (b), respectively.

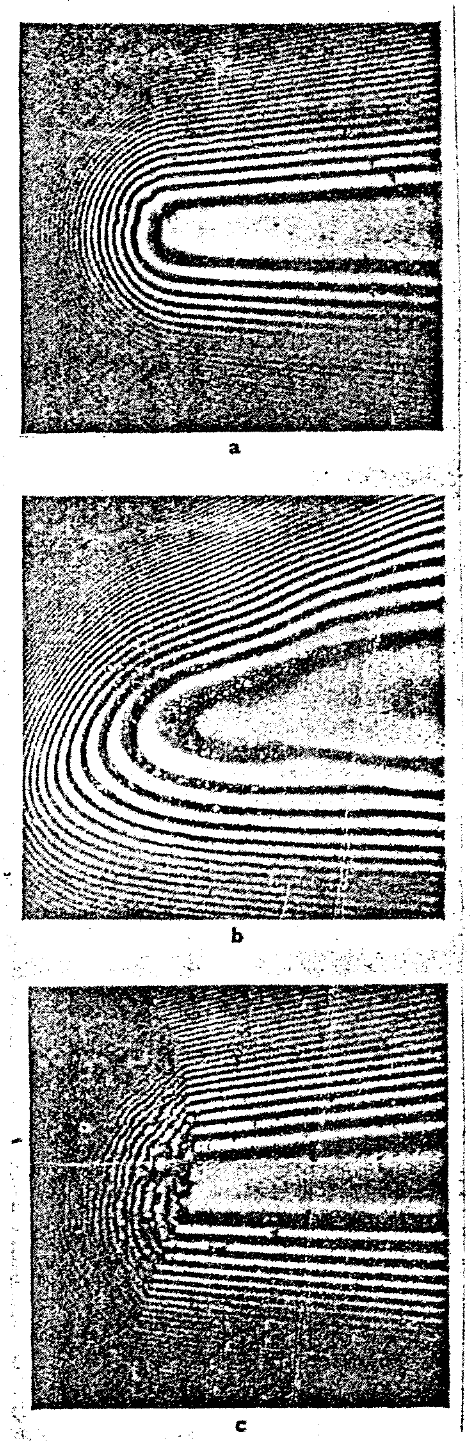


Fig. 58. Interferograms of typical blendings between the conical and spherical part of Rockwell C indenters.

(For better quality pictures, see the originals [Y-12, T-2 and T-3].)

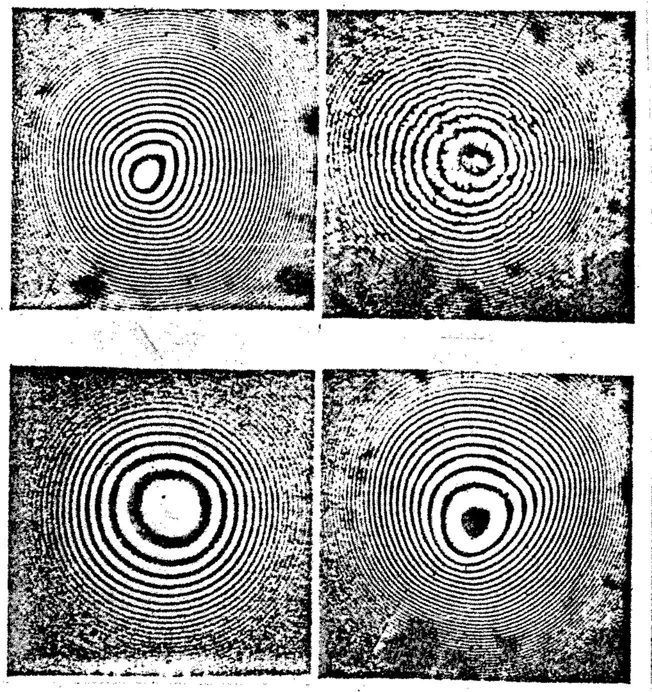


Fig. 59. Interferograms of the spherical point of Rockwell C indentors.

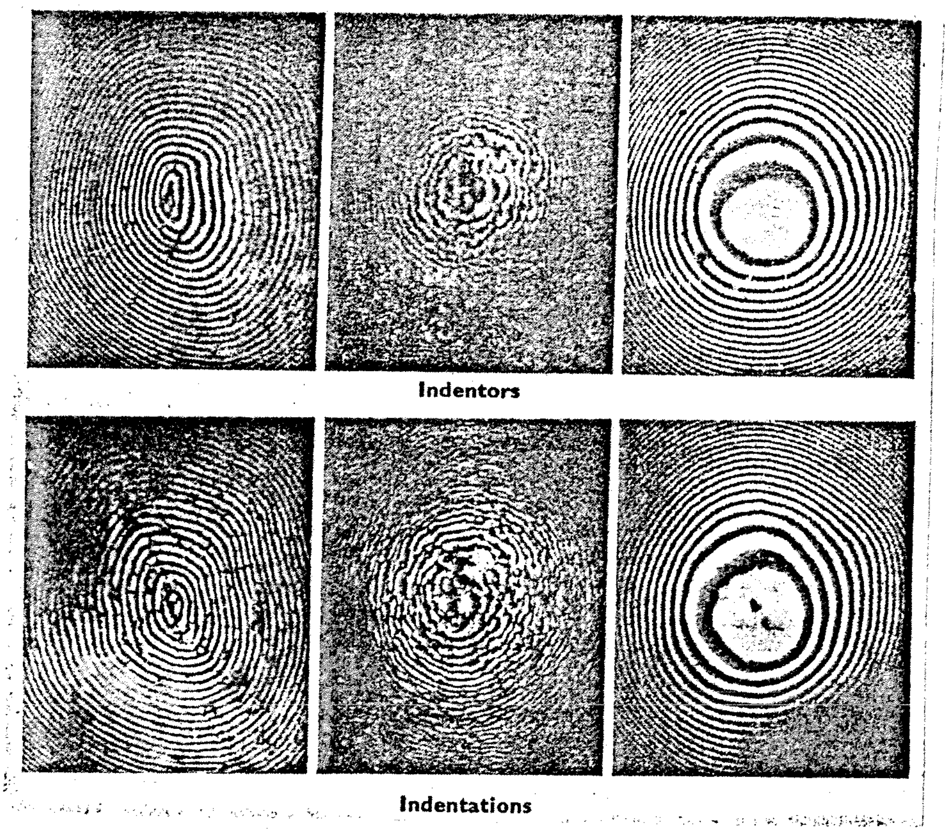


Fig. 60. Interferograms of the tips of indentors and of the corresponding 'tips' of the indentations

(For better quality pictures, see the originals [J-1 and T-2].)

From the interferogram of the tip the approximate value of the radius at the extreme tip of the indenter can be determined. The calculation method is given in [J-1]. The error of this method is given as about 4% at the average, and 7% at the maximum.

TOLMON and HALL [T-2] compared the interferogram of the tip of an indenter with that of the indentation made by it. It can be seen in Fig. 60 that the form of the indenter is faithfully reproduced in its indentation in the region of the tip and of the blending.

The restricted axial distance of the zone of the spherical indenter that can be examined by the interference method can be increased if the optical flat plane used e.g. in Fig. 53 to produce the interference fringes is replaced by the mirror like surface of a steel ball of ∅ 0,4 mm. The optical system of the micro-interferometer described by YAMAMOTO and IWASAKI [Y-3] is shown in Fig. 61. Light source S is imaged by lenses L_1, L_2 and L_3 in the plane of the iris diaphragm S_1, after having passed interference filter F. S_2 is another iris diaphragm controlling the area of the field of view. S_1 is at the front focal point of the lens system of L_4 and L_5, consequently a parallel beam of light emerges from L_5. Beamsplitter P reflects half of this light, while transmitting the other half. The reflected beam is focused by microscope objective Ob 1 on the apex surface of diamond penetrator A being tested. The light reflected by A is parallelized by objective Ob 1 and its portion transmitted by P is focused by lens L_6 and L_7 in the focal plane of the microscope eyepiece E. The part of the light transmitted by P is focused by Ob 2 (identical in design and focal length with Ob 1, magnification 48 x) on the smooth surface of steel ball B. The reflected light passes Ob 2 again, then it is reflected by P to meet the first half of the split light beam, forming interference fringes in the focal plane of eyepiece E.

Fringes are concentric if the difference of the radiuses is small and the tip of the tested indenter is exactly spherical. In the case of surface irregularities interference fringes indicate the deep or high spots (Fig.62). The deviation from the reference surface can be constructed in various axial sections as shown in the lower part of Fig. 62. The field of vision of ∅ 0,2 mm of this apparatus embraces the complete spherical part of the Rockwell C indenter.

YANO et al. [Y-12] used a ∅ 0,5 mm reference ball on the same apparatus, i.e. the indenter of ∅,2 mm nominal radius was compared with a reference radius of 0,25 mm.

IIZUKA and IMAI [I-1] used the same method for the evaluation of balls employed at Shore hardness tests, having a diameter of 2 mm. The balls were examined also with various other methods and the results, as well as error characteristics compared.

8.4. Autocollimation method for cone angle measurement

The apparatus developed by MEYER and Messrs LEITZ, WETZLAR [M-16] for the measurement of the cone angle of Rockwell C indenters and of the angle between the pyramid faces of Vickers indenters is shown in Fig. 63 schematically. It is composed of an interference microscope, of a tilting equipment, and of an autocollimating telescope. The indenter to be measured (9) is clamped on the tilting equipment, together with the mirror prism (11). The exchangeable prisms have angles of 120° and 136°, for Rockwell and Vickers indenters, respectively. In the scheme 2 represents the eyepiece of the interference microscope, 5 and 7 the objectives. 3 and 4 are beamsplitters, 6 the referenc mirror. 1 is a possible camera connection and 8 the light source.

In the autocollimating telescope part 14 is the eyepiece, 17 the objective, 12 the light source. 16 is a beamsplitter and 13 the cross lines.

In Position 1 of the tilting equipment the telescope scale is zeroed. If the indenter and the prism are tilted around their common axis into Position 2, the mark in the telescope eyepiece indicates any deviation of the cone angle from the nominal value, materialized by the mirror prism. The measuring scale has a 1' graduation, with possibility of estimating 0,1'. For the adjustment of the two positions of the tilting equipment an interference microscope is used. The flank of the cone of the indenter is adjusted into a position perpendicular to the axis of the microscope. In this position interference patterns similar to those shown in Fig. 57 (a) can be seen. Simultaneously with angle measurement this pattern permits a checking of flank length and quality.

The uncertainty of angle determination on this apparatus (two standard deviations) was found to be ± 1,5' [J-1] .

A similar apparatus was described by LUCZYWEK [L-5]. The mirror prism suited for both Rockwell C and Vickers indenters is shown in Fig. 64.

8.5. Microscopic collimation for radius measurement

Microscopic collimation, as employed for measuring the radius of the spherical part of indenters was described by YAMAMOTO [Y-3, Y-5, Y-6] and YANO et al. [Y-12].

The working principle of the method, known also as Guild's mirror method, is shown in Fig. 65. The sphere of radius r can be displaced along the optical axis of the microscope. An image can be observed in eyepiece E in two axial positions of the sphere : when its surface is at the object point of objective Ob (center of the sphere at O_2), or when the center of the sphere is at the object point (O_1). The distance between the two positions corresponding to sharp images is equal to the radius of the sphere. If a HRC indenter is arranged at the place of the sphere, the mean radius of the spherical part can be determined. It was found, however, that different values are obtained if the numerical aperture of the objective is changed. Fig. 66 shows that different apertures correspond to different angles of vision. Only numerical apertures > 0,5 include the whole spherical part of the indenter. The microscopic collimation method supplies the mean value of the surface included, accordingly if the radius is not uniform on the whole spherical part, different mean values will be obtained with different apertures. For purposes of standard indenter those ones were selected in the case of which the obtained mean radius value did not depend on the numerical aperture. The standard deviation of repeated measurements was found to be 2,5 µm to 1,3 µm for numerical apertures of 0,2 to 0,65, respectively [Y-8] .

A detailed analysis of the possible accuracy of the method is given in [Y-3].

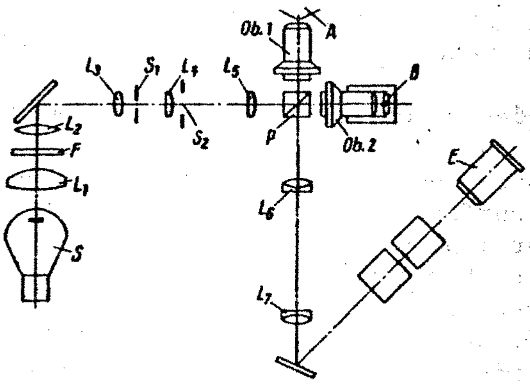


Fig. 61. Micro-interferometer with spherical reference surface

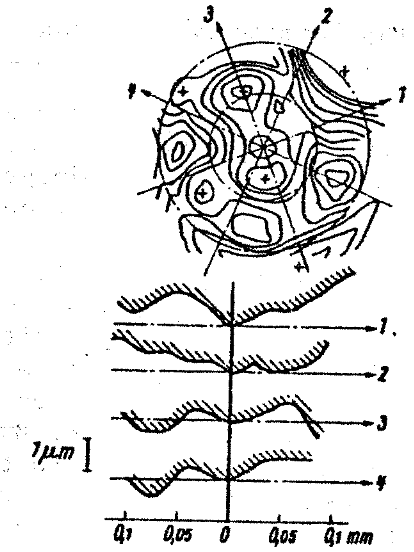


Fig. 62. Interferogram obtained by the apparatus shown in Fig. 61, and the deviations of the indenter surface from the nominal sphere.

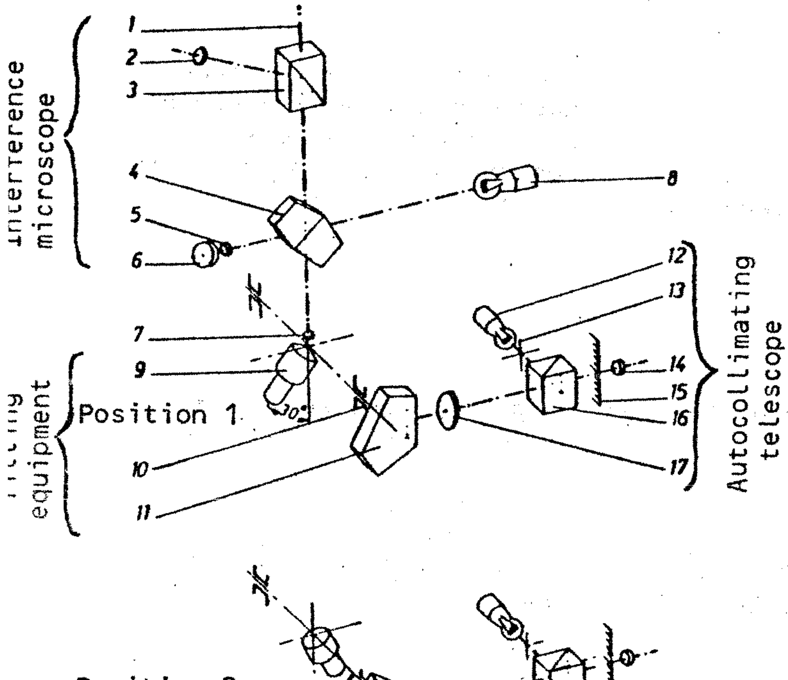


Fig. 63. Cone angle measuring apparatus using the autocollimation method

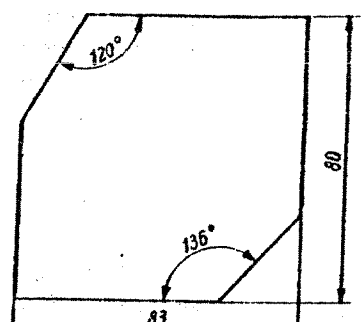


Fig. 64. Mirror prism for indenter angle measurement by the autocollimation method

8.6. The 'Laminogram' method

The method was proposed and developed by GIDEL [G-1, W-1, P-15, M-12]. Interferograms made of diamond indenters include only a small section of the surface. The laminogram includes the whole working surface of the indenter, therefore it was named by some researchers a 'macro-interferogram'.

By the indenter to be tested an indentation is made in a soft metal plate (e.g. brass) on the surface of which fine metal powder has been previously dispersed. After having removed the indenter, the line of section between indenter surface and the upper surface of the metal plate appears as a bright curve formed by adhering metal powder, if observed in incident light on a microscope. By utilizing this phenomenon the indenter is repeatedly impressed into the metal surface to predetermined, steadily decreasing depths (e.g. 300, 250, ... 100, 50 µm). In this way we obtain a set of curves on the surface of the indenter, named the 'laminogram,' which is similar to contour lines of maps. Each line represents the cross section of the indenter at the given depth. From the photographs of the laminogram the geometrical values of the indenter can be calculated according to the method given in [G-1] and [P-15]. Fig. 67 shows laminograms of good and bad quality Rockwell C indenters. Fig. 68 shows laminograms of Vickers indenters prepared by MIKOSZEWSKI [M-20]. Photo a) shows that the diamond tip of the indenter was displaced in the mounting. At later examinations the angle between the pyramid axis and the shank axis was found to be about 1°, therefore this indenter was discarded. Photo b) shows a good Vickers indenter. The preparation of the laminogram can be facilitated by employing a special press described in the above-cited references, but even so the method is relatively time-consuming.

8.7. Microstereophotogrammetry

LAYTON [L-2] applied photogrammetry to the quantitative examination of small three-dimensional objects, such as hardness testing indenters. By this method a very detailed examination of the surface is possible, by mapping the contour lines, as shown by three examples given in Fig.69. Results are considered to have mean standard deviations of the order of 2 µm.

8.8. Contour tracing method

The circular cross section of the conical part of Rockwell C indenters was examined by TOLMON and HALL [T-2, T-3] by the use of the Talyrond roundness tracing machine. A special design of the stylus was necessary which engaged the cone normal to the flank, but the plane of measurement was so arranged as to be perpendicular to the axis of the indenter. Tracings of typical Talyrond charts taken on the flanks of indenters are shown in Fig. 70. Both charts have a radial magnification of x 2000.

Care must be exercised when interpreting the Talyrond charts on account of the distortion due to the high radial magnification. In the examples shown, the departure from circularity is 0,01 and 0,02 mm respectively, the departure being defined as the difference in diameter of two imaginary coplanar concentric circles such that the annular space between them would just contain the profile of the surface under test.

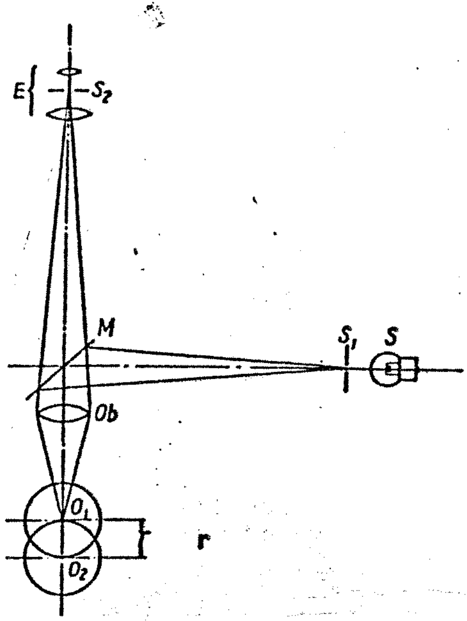


Fig. 65. The optical system of microscopic collimation

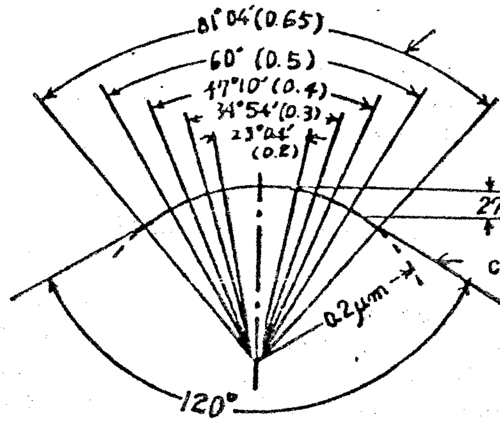


Fig. 66. Section of the spherical part of the Rockwell indenter included in the case of different numerical aperture values

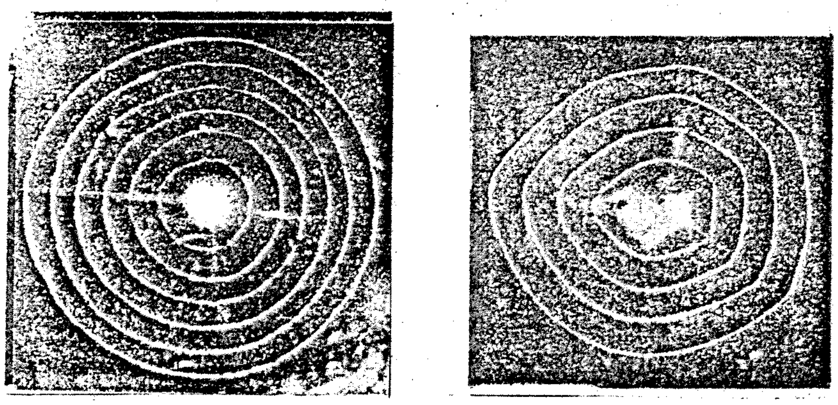


Fig. 67. Laminograms of two Rockwell C indenters
a) Circular b) rounded hexagonal
cross section

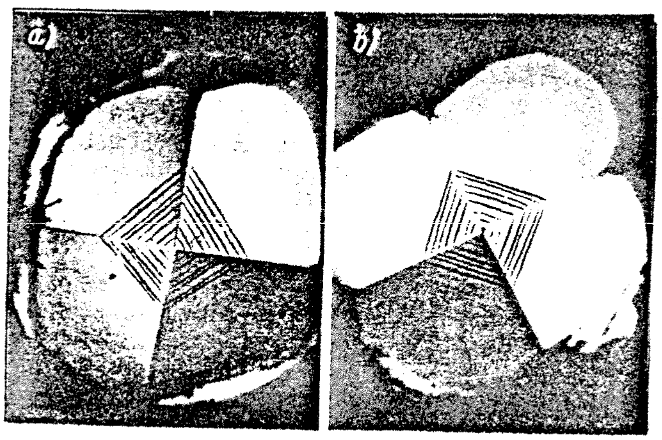


Fig. 68. Laminograms of two Vickers indenters
a) Axial displacement b) Good

In tests on a number of indentors, considerable variation in circularity was found. In the best case the error in circularity was 0,005 mm (see also Fig.28).

8.9. Inspection of surface quality

Freedom from surface defects, cracks, and signs of wear can be checked on a measuring microscope. KERSTEN [K-3] and MIKOSZEWSKI [M-20] recommend the use of incident light dark-field illumination. To ensure a satisfactory illumination an adjustable and revolving indenter holder (Fig.71) should be used. By rotating the indenter one can find the best light conditions for detecting defects inside the diamond too, though these are sometimes without influence on the performance of the indenter.

Defects on the surface of the diamond directly influence measured hardness values. Defects inside the diamond may result in a shorter life of the diamond. A stereo-microscope is preferable if no photos are taken. One-sided illumination by an adjustably arranged light-source permits to adjust the best contrast to find the diamond defects. Magnifications of 30 x to 120 x are recommended in [K-3], [P-15], [SR-37], and [SR-24].

Before microscopic examinations the diamond surface should be de-greased carefully.

During the visual inspection of the indenter the surface condition of the shank and of the supporting surface of the diamond holder should also be examined.

WEINZ and REUMUTH [W-14] used a stereoscan electron microscope to prepare photos of the indenter surface with magnifications up to 2100 x. Surface roughness of diamonds manufactured by different methods was plotted by the Perth-O-Meter. A comparison of hardness values obtained by indenters of different surface roughness values showed no significant difference. Therefore production technologies ensuring better roundness by higher surface roughness are considered to be preferable to high-polish surface which may eventually cause form deviations.

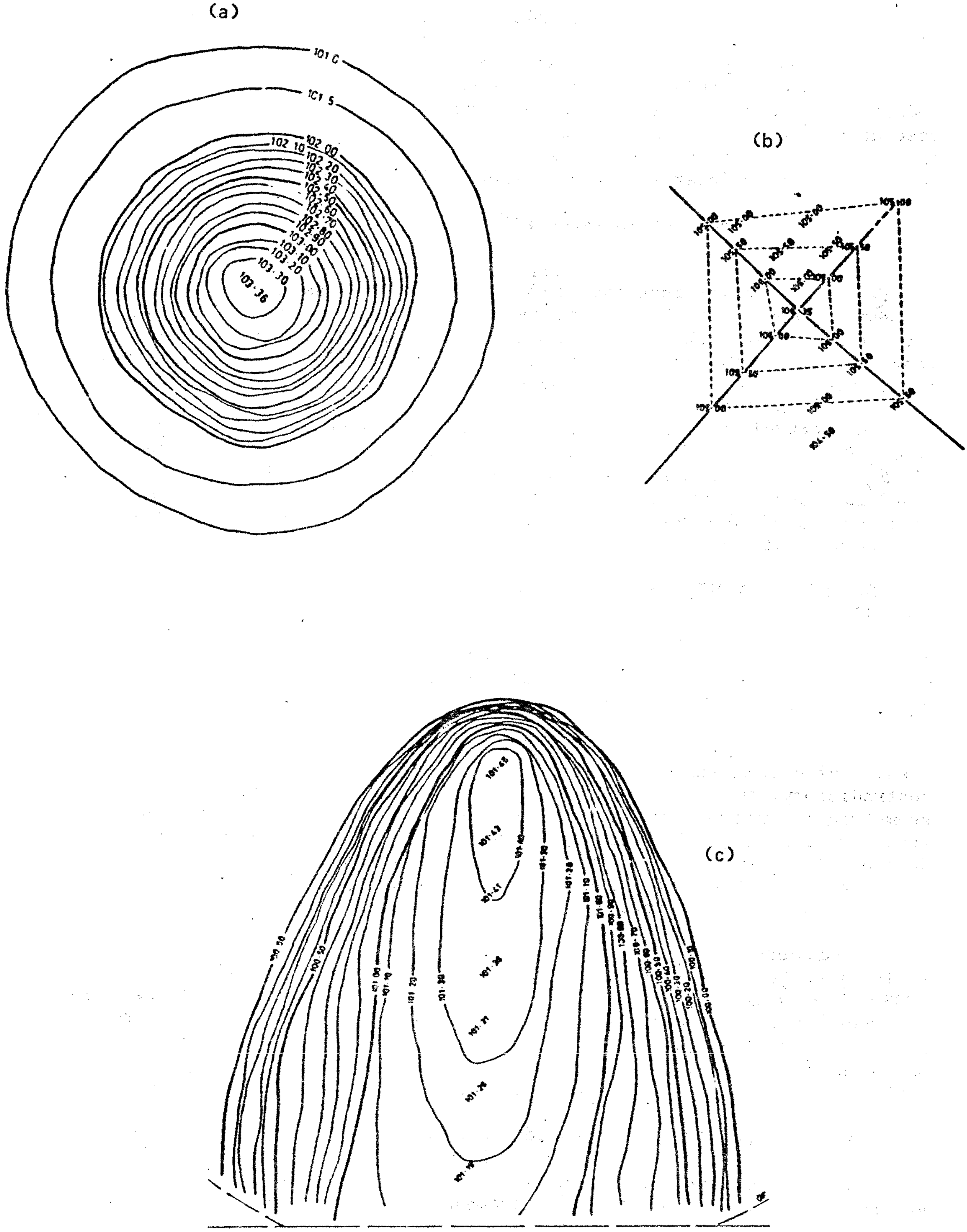


Fig. 69. Microstereophotograms of indenters

a) Rockwell C, b) Vickers in axial direction,
c) Rockwell C in a direction perpendicular
to the cone flank.

9. Performance test of the indenter

The performance test of the indenter consists of making hardness measurements on test blocks on a standardizing machine, and repeating the measurements by using a standard indenter under identical conditions. The difference of hardness values obtained by the tested and the standard indenter is characteristic for the performance of the indenter, it can be used as a correction value during later use. It should be noted that the difference depends on the measured hardness level, therefore it is not sufficient to determine it on a single block.

The performance test is especially important in the case of the Rockwell C method.

According to international standard specifications [SR-11, SR-24, SR-45], an indenter should be rejected if, during the performance test, the hardness values obtained differ by more than 1 Rockwell unit (in the range 30 to 65 HRC) from those of the standardized blocks calibrated with an accepted (standard) indenter (mean value of five indentations).

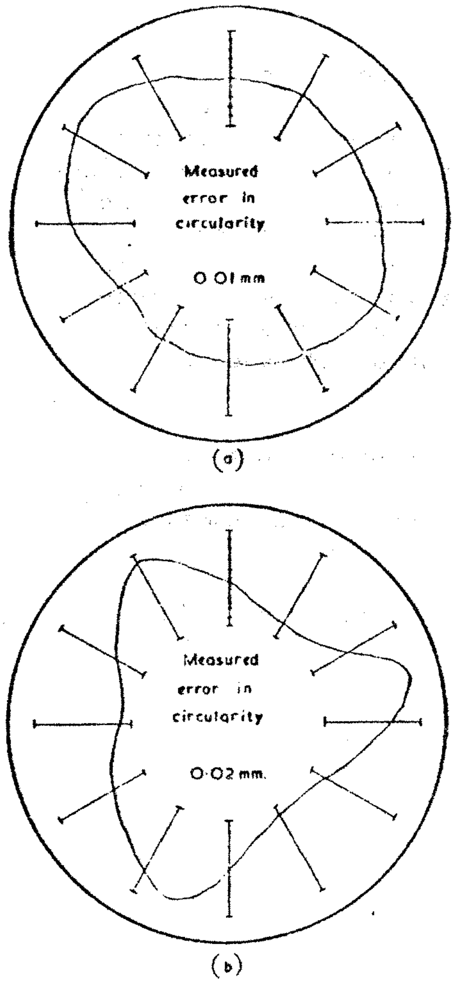
For Rockwell superficial tests the difference should not be more than 1 Rockwell superficial unit in the range of 40 to 80 HR 30 N [SR-12, SR-45] . The maximum permitted differences specified in [SR-37] for standard indenters are the following : ± 0,5 HRC, ± 0,5 HRA, ± 1 HRN (mean values of 10 indentations). Wood et al. [W-21] specify ± 0,5 HRC for the mean of five indentations.

H. and T. YAMAMOTO [Y-18] compared the performance tests of HRC and HRB indenters. Whereas the range of deviations of several HRC indenters is practically constant over the whole hardness range (Fig. 72), the range for HRB indenters is considerably reduced as hardness increases. Differences in the performance of HRB indenters are attributed to the ball holder and not to the ball.

The main problem connected with indenter performance tests is that results of performance and those of the geometrical examination may be contradictory. An indenter being inside the tolerance limits for the geometrical parameters may exceed the tolerance limits for the performance test, or vice versa. That is why the performance test has been disputed for decades. It is impossible to review all the references on this subject, only some characteristic points of view are cited here in the chronological order of their publication.

FLURSCHÜTZ (cited in M-17) was convinced of the usefulness of the performance test, even at the expense of the geometrical examination. ROSSOW [R-11] examined the influence of the uncertainty of geometrical measurements on the hardness value. Consequently, in the case of an uncertainty of ± 0,01 mm for the radius measurement, the performance test may be better. If cone angles can be measured with an uncertainty of ± 6', the geometrical measurement is better than the performance test.

YAMAMOTO and YANO [Y-6] consider a hardness testing machine to be so sensitive to detect the difference between the performance of indenters that hardness measurement is superior to checks by ordinary form error measurements. YANO et al. [Y-12] recommend, in the case of indenters used



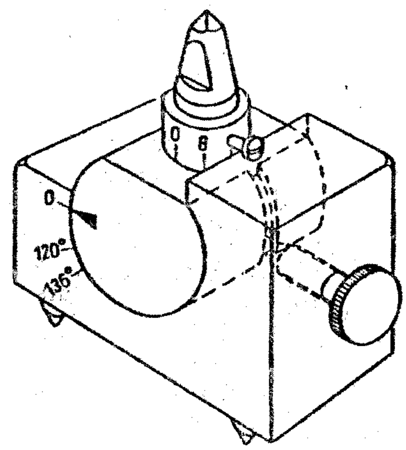


Fig. 71. Indenter holding fixture used for the examination of surface quality of indenters on a microscope.

Fig. 70. Talyrond charts taken on the flanks of indenters. Originals, twice the size reproduced here, were at x 2000 radial magnification.

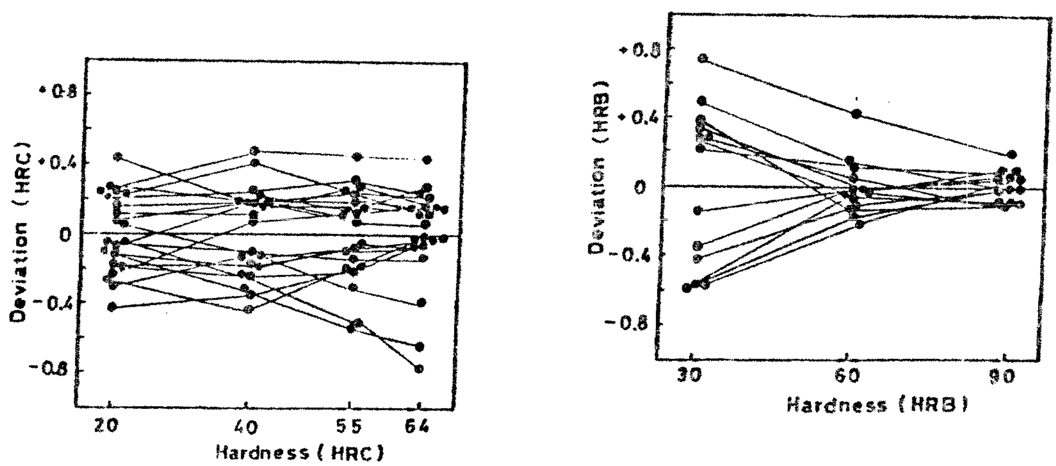


Fig. 72. Comparison of the range of deviations at the performance tests of Rockwell C and B indenters.

in commercial hardness testers, to perform complicated geometrical form measurements only on those indenters which have already passed the performance test.

MEYER who is considered to be the first to employ performance tests on the first standardizing equipment, later changed his opinion and objected the performance test on economical reasons, based on an experiment described in [M-17] . He considers the geometrical examination as sufficient. KOVÁCS [K- 8] analysed statistically the results of performance tests and geometrical examinations of indenters. In the case of contradictions the following procedure is employed in his Institute : if geometry is outside, while performance inside the tolerance, the indenter is accepted. If geometrical parameters are inside tolerance limits, the acceptance limits for the performance test are increased to ± 1,3 HRC at 60 HRC and to ± 1,5 HRC at 30 HRC.

MIKOSZEWSKI [M-22] considers the performance test useful within a single state, but not yet applicable in the international trade, because systematic differences between national hardness standards are sometimes higher than the tolerances specified for the performance test.

According to WOOD, COTTER and NASH [W-21] a conclusive inspection of the geometric form is at present impossible, so that the performance test must of necessity be an integral part of the inspection procedure.

This selection from the divergent opinions shows that there is still much research work to do in the field of the geometry and performance of indenters.

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STANDARDS AND RECOMMENDATIONS

SR - 1 ISO/R 80-1968 Rockwell hardness test (B and C scales) for steel.

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SR - 8 ISO 6506-1981 Metallic materials - Hardness test - Brinell test

SR - 11 ISO/R 716-1968 Verification of Rockwell B and C scale hardness testing machines.

SR - 12 ISO/R 1079-1969 Verification of Rockwell superficial N and T scale hardness testing machines.

SR - 15 ISO/R 674-1968 Calibration of standardized blocks to be used for Rockwell B and C scale hardness testing machines.

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/R 640-1967 Calibration of standardized blocks to be used for Vickers hardness testing machines.

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

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SR - 25 OIML IR N°12. Verification and calibration of Rockwell C hardness standardized blocks.

SR - 26 OIML IR N°11. Verification and calibration of Rockwell B hardness standardized blocks.

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SR - 49 EURONORM 127-77 Calibration of standardized blocks to be used for Vickers hardness testing machines.

SR - 50 EURONORM 128-77 Calibration of standardized blocks to be used for Brinell hardness testing machines.

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