FACTORS INFLUENCING HARDNESS MEASUREMENT

(A systematic survey of research results)

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PREFACE

In the field of the metrology of hardness scales, many research results were published in the last decades in technical journals and conference reports. In the bibliography entitled The Metrology of Hardness Scales, published in 1981 by the International Bureau of Legal Metrology, 155 papers were listed. This high number of publications shows the interest of research workers in this field, and further, that a collective research activity has been developed over the last thirty years. Sometimes research teams were organized for the solution of some specific problems. The results published in various journals, in different languages, are not easily accessible to other researchers interested in a given subject. The above mentioned bibliography can serve as an initial help but the title of a publication cannot be sufficiently comprehensive, and cannot summarize the whole content of the publication. It is possible that experiments are repeated, which were already performed somewhere else, but the results are not generally known, or even have already been forgotten. A monographic treatise on the metrology of hardness is missing, though the quantity of published data would permit the compilation of a comprehensive work on the subject.

Another problem with the dispersed publications is the question of language. Only works published in English, French, German and Russian were included in the bibliography, with a few, really significant exceptions. There are, however, numerous other publications on the metrology of hardness in other languages, which are not generally known, especially in Japanese, also in Czech, Hungarian, Italian, Polish, Rumanian, to mention only a few of them.

The present work is an attempt to collate the dispersed research results from a narrow section of activities in the field of the metrology of hardness scales, and to make them available in a more or less unified presentation. The reader has the possibility of studying the original publication more in detail.

It was interesting to find how many similar experiments were carried out. The results are sometimes easily comparable, but there were cases where the form of presentation used by different authors was so divergent that an actual conversion of data was first required to be able to deal with them on a unified basis.

The narrow section selected for treatment, from the wider field of the metrology of hardness scales, was the effect of some influence factors on hardness measurement results. Measurements never supply the 'true value' of the measured quantity, the result is always influenced by other quantities. In this presentation the research results are summarized systematically, in a form that permits their use in metrological practice. An attempt has thereby been made to separate major and unimportant results, and to indicate, as far as possible, development trends and future aims.

It should again be emphasized that the present work is a summary of the results of 56 research workers listed in the Index, to whom the author wishes to express his appreciation. Any comments on the text, proposals or additions are welcome and appreciated.

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Assistant Director

CONTENTS

1. GENERAL INTRODUCTION

1.1. 'Hardness' as a 'measurable quantity'

Hardness as a property of materials is much disputed as regards its character (P-18). It is indisputable that hardness values cannot be derived from base quantities and it is consequently not a physical quantity. But it is a very important technological characteristic, a numerical value for which is indispensable, eg. in machinery production. It should be stated, before going into a discussion of terminology, that the determination of hardness values, and the uniformity of determinations all over the world is a 'must' in up-to-date technology. Besides hardness there are many properties of objects which are not physical quantities, for which, nevertheless their values should be determined; they should be tested or measured, this being a requirement of technology. Such properties include surface roughness, colour and numerous other examples of materials testing. The term 'hardness' if used alone, is a concept of everyday life. It has no definition. Only by adding a further qualification, such as 'Vickers hardness', does it become a defined term.

According to the BIPM-IEC-ISO-OIML International Vocabulary of Basic and General Terms in Metrology (Draft, March 1983), a 'measurement' (2.01) is 'the set of operations having the object of determining the value of a quantity'. The term 'quantity' is defined (1.01.) as 'an attribute of a phenomenon, body or substance which may be distinguished qualitatively and determined quantitatively'. These two definitions can be employed for the determination of hardness, just as well as the 'value of a quantity' (1.17) which is the 'expression of a quantity in terms of a number and an appropriate unit of measurement'. For hardness the term 'reference-value scale of a quantity or property' given under 1.21 in the Vocabulary is important : 'For a given quantity or property, a set of values determined in a defined manner and accepted by convention'. The scale of reference of hardness can be formulated as a set of numbers that indicates the degree to which hardness is inherent in materials, the numbers having been assigned to the results of a prescribed comparison procedure which defines the property of hardness implicitly. Several different relative hardness scales have been defined (Brinell, Rockwell, Vickers, Shore, etc.). Each of these scales orders points of relative hardness by reference to different criteria and by a different comparative procedure. The numbers arbitrarily assigned to the points on each scale only indicate relative position within such an order. They do not quantify the property or relate it to a unit.

Values on a scale of reference characterise, beyond doubt, no 'physical quantities', but we should speak of hardness as a 'conventional quantity'. There may be ambiguities of terminology, but this is not the greatest problem in the field. For economically important practical purposes, exactly reproducible numerical values of hardness are required.

1.2. The place of hardness measurement in Metrology

The hardness value is the result of an experiment performed under standard conditions, and is based on a convention. The process of hardness determination comprises two steps :

(i) an experiment performed under prescribed circumstances (producing the indentation), and

(ii) the determination of a characteristic dimension of the indentation (length measurement).

Hardness value H is the function of the measured length 1, and of the physical quantities forming the prescribed conditions of the experiment (length values l_i, angle values α_j, time values t_k, velocity values v_l, force values F_m, where subscripts i,j,k,1,m = 1,2,3 ...).

$$H = f(l, l_i, \alpha_j, t_k, v_l, F_m) \quad \ldots (1)$$

Although the hardness value H is not a physical quantity and as such it cannot be expressed in terms of SI units, all quantities appearing on the right side in Eqn (1) are physical quantities and are expressed in SI units.

The definition formulae of hardness testing methods, as fixed in standard prescriptions, are of the form

$$H = f(l) \quad \ldots (2)$$

Thus, hardness is defined as the function of a single auxiliary quantity, length. All the other variables indicated in Eqn (1) are supposed to be at nominal values. One of the aims of metrological research work in connection with hardness is the determination of the effects on the hardness values of deviations in these quantities from nominal values (inside the tolerance limits specified in standards, or exceeding them). This means the determination of the following functions :

$$\frac{\partial H}{\partial l_i} \quad \text{and} \quad \frac{\partial H}{\partial \alpha_j} \quad \ldots (3)$$

characterising the indenter geometry,

$$\frac{\partial H}{\partial t_k} \qquad \frac{\partial H}{\partial v_l} \quad \ldots (4)$$

characterising the test cycle, and

$$\frac{\partial H}{\partial F_m} \quad \ldots (5)$$

characterising the inaccuracy of loading.

For a better understanding of the character of the scale of reference of hardness, some of its properties should be examined, and analogies or contrasts with scales of some physical quantities investigated.

The scale of reference of hardness is a continuous scale, like the scales of physical quantities. The measured hardness, however, cannot be increased continuously, as for example a given length or temperature can be increased by arbitrarily small increments, and a suitable length or temperature measuring instrument can follow these changes of the measured quantity continuously. Hardness is, in turn, a property of the material resulting from a technological procedure (heat treatment), which cannot be continuously increased or reduced. Even long-time recrystallisation phenomena which may cause a slow continuous change of hardness (ageing, alteration) cannot be followed by the hardness measuring equipment, because the determination of hardness is not repeatable since it causes a local destruction of the measured object, however small and, for practical purposes, negligible this destruction may be.

For hardness measurements we take a sample of the tested surface, the individual points of which may have more or less different hardness values. This local variation causes some metrological problems in the case of standardized hardness blocks. In addition to the macro-variation of hardness value, there is a micro-variation of hardness within the relatively small area of the indentation caused by the different crystals forming the tested object. Actually the hardness value determined by an indentation process is the average of hardness values of different crystallographic components comprising the 'sample' covered by the indenter.

Another characteristic of the scale of reference of hardness is that values are not additive. We can say that 2 m + 3 m = 5 m, but 20 HRC + 30 HRC $\neq$ 50 HRC. This follows from the fact that hardness value cannot be interpreted as the product of a number and of a unit.

In metrological research work connected with hardness scales questions like the following should be answered :

- How are set up and maintained the hardness scales?
- How are reproduced the hardness scales at other places?
- What are the values characterising the repeatability and reproducibility?
- How to ensure that hardness values measured on the same object in different laboratories could be arranged at the same point of the hardness scale?

Accordingly the OIML bibliography mentioned in the Preface included publications on the subjects :

- Establishing, maintaining and comparison of hardness reference scales,
- Factors influencing hardness values (instrumental and personal),
- Errors at various stages of the hierarchical order of hardness measurement.

The present work deals with the instrumental part of the second subject.

1.3. International cooperation

The following sections of international organizations are most active in the field of the metrology of hardness :

OIML Reporting Secretariat SP 19-Sr 3 Hardness (reference blocks and testing machines). Responsible Member State : Austria

OIML Reporting Secretariat SP 19-Sr 4 International hardness reference base. Responsible Member State : Czechoslovakia

OIML Reporting Secretariat SP 19-Sr 6 Terminology (Characteristics of materials). Responsible Member State : Hungary

ISO Sub-Committee TC 164/SC 3 Hardness testing. Secretariat : SIS, Sweden.

IMEKO Technical Committee TC 5 'Hardness Measurement'.

Beyond these several regional international and national organizations are contributing to the advancement of hardness measurement.

2. SYSTEMATIZING ERROR SOURCES

The error sources of standard hardness measuring equipment can be grouped in various ways. As to the character of sources resulting in errors, three groups can be differentiated :

a) constant error sources, mostly arising from the design of the machine, resulting in systematic errors,

b) error sources which can be made constant by suitable control of the machine, similarly resulting in systematic errors,

c) sources resulting in random errors.

The classification of error sources shown in Table 1 has three main groups, namely the specimen, the equipment and the measuring person. The importance of the individual sources is different for different hardness measurement methods. The degree of importance is indicated in this table by using three symbols. One could say that every effect is important in standardising work. This is actually so and metrologists should strive to achieve optimum conditions with respect to each effect. The symbols used in the table are intended only to express the relative importance of the various factors. The degree 'low' has not been employed at all, with respect to standardising measurement.

The letters (a), (b) and (c) in the table refer to the character of the effect, as enumerated previously.

In hardness standardizing work the specimen is the standardized hardness block. Evaluation of measurements greatly depends on surface quality of the block for the Vickers measurement, therefore a higher importance has been attributed to this effect. Hardness ununiformity of the block is of a random character.

The effect of the hardness standard equipment can be subdivided into design, loading,indenter and measuring equipment effect. The design of the machine is of primary importance, just as well as the functioning of the loading mechanism. The load may have both systematic and random errors, though in standards systematic errors of load should be eliminated. The indenter has often a systematic error which is accounted for by a correction. At Brinell measurements the use of commercial standard balls somewhat reduces the importance of this error source. The measuring equipment is similarly of lesser importance on account of the greater dimensions of Brinell indentations.

The effect of the person performing the measurement can be important though automatic control tends to reduce the effect of the human factor. The correct adjustment of the measuring equipment is of course very important requirement, but in standardising work reliable and skilled machine operators can be assumed to be available. The actual performing of the indentation process is mostly controlled on most hardness standard equipment, thus point 3.2. could have actually been transferred to 2. The recent tendency of up-to-date hardness standard equipment is to perform also the measurement of the indentation automatically, consequently point 3.3. can also be transferred soon to 2.4.

Table 1 clearly shows that with gradual automation of hardness standard equipment the personal factor tends to be eliminated.

In the followings the effects of the individual factors will be examined separately.

Table 1

ERROR SOURCES AT HARDNESS STANDARDISING MEASUREMENTS

	Importance HR	 HV	 HB	Character of error
1. Specimen (standardised hardness block)	◓	●	◓	(c)
2. Equipment				
2.1. Design	●	●	●	(b) (c)
2.2. Loading mechanism	●	●	●	(a) (c)
2.3. Indenter	●	●	◓	(a) (c)
2.4. Measuring equipment	●	●	◓	(a) (c)
3. Measuring person				
3.1. Adjustments on the equipment	◓	◓	◓	(c)
3.2. Performing the indentation process	◓	◓	◓	(b)
3.3. Measuring the indentation	●	●	◓	(b) (c)

Degree of importance
(symbols)

● high
◓ medium
○ low

3. TEST FORCE

3.1. Rockwell hardness test (C scale)

Increased preliminary test forces result in higher apparent hardness values, since the penetration depth serving as the basis of measurement (zero setting of the instrument) is greater. Higher total (or additional) test forces, in turn, result in lower apparent hardness, as the total penetration depth will be greater.

The effect of test force errors was examined experimentally by PHILLIPS and FENNER (P-13), HILD (H-3, H-4), ZAYTSEV and SLAWINA (quoted in P-14), YAMAMOTO-YANO-YAZIMA (Y-4), PETIK and KOVACS (P-3). YAMASHIRO and UEMURA (Y-9) made also a theoretical analysis and elaborated a calculation method. All the valuos measucalcur calculated by theae researchers can be arranged in the shaded areas shown in Fig.1, where the change of hardness resulting from increasing the preliminary and the total test force by 10 N is shown in function of the hardness level. It is evident that at lower hardness levels, the effect of test force errors is higher.

It should be noted that the change of penetration depth in consequence of a small change of the preliminary test force is sensitive to the state of the upper layer of the specimen, which may be inhomogeneous in depth.

For the sake of convenience the values given in Fig. 1 are related to test force errors of 10 N. For other forces interpolation should be employed. Within the range of permitted errors for hardness testers (0,5% for additional, and 2% for preliminary test force) a linear relationship between force error and the resulting error in the hardness value can be assumed. For test forces differring from the prescribed values by a greater amount, a linear relationship was found (H-4) between the error in hardness value and the square root of the additional test force.

3.2. Rockwell hardness test (B scale)

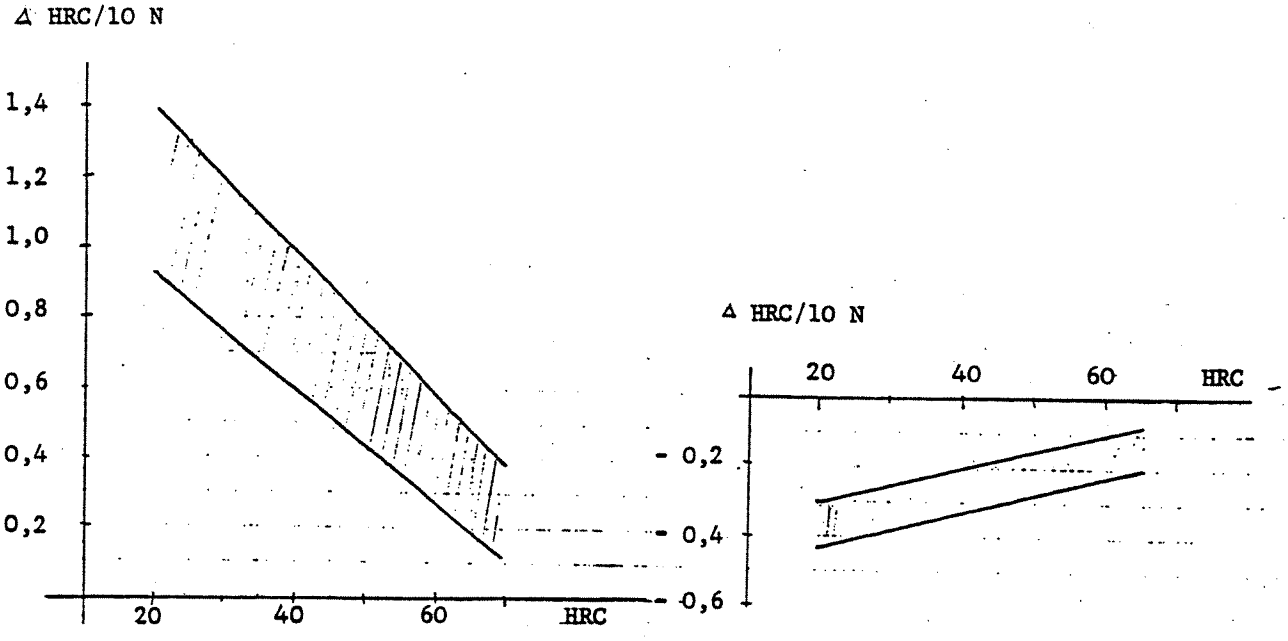
The effect of test force errors at HRB tests, performed with a steel ball, was examined both theoretically and experimentally by YAMASHIRO and UEMURA (Y-9). A linear correlation was found between test force error and the resulting hardness errors, the signs of errors are, of course, similar as in the case of HRC measurement. The relationship between hardness error and hardness level is also a linear function, namely for the preliminary load :

$$\Delta \mathrm{HRB} = 0{,}136\ (130 - \mathrm{HRB})\ \frac{\Delta F_o}{F_o} , \qquad (6)$$

where HRB denotes the hardness level, Δ HRB the error in hardness at the effect of an error ΔF_o in the preliminary test force F_o .

For the total test force F the function is found to be :

$$\Delta \mathrm{HRB} = -\ 1{,}01\ (130 - \mathrm{HRB})\ \frac{\Delta F}{F} . \qquad (7)$$



(a)

(b)

Fig. 1

a) Error in the HRC hardness value at the effect of an error of 10 N in the preliminary test force F_0, in function of hardness level.

b) Error in the HRC hardness value at the effect of an error of 10 N in the total test force F_1, in function of hardness level.

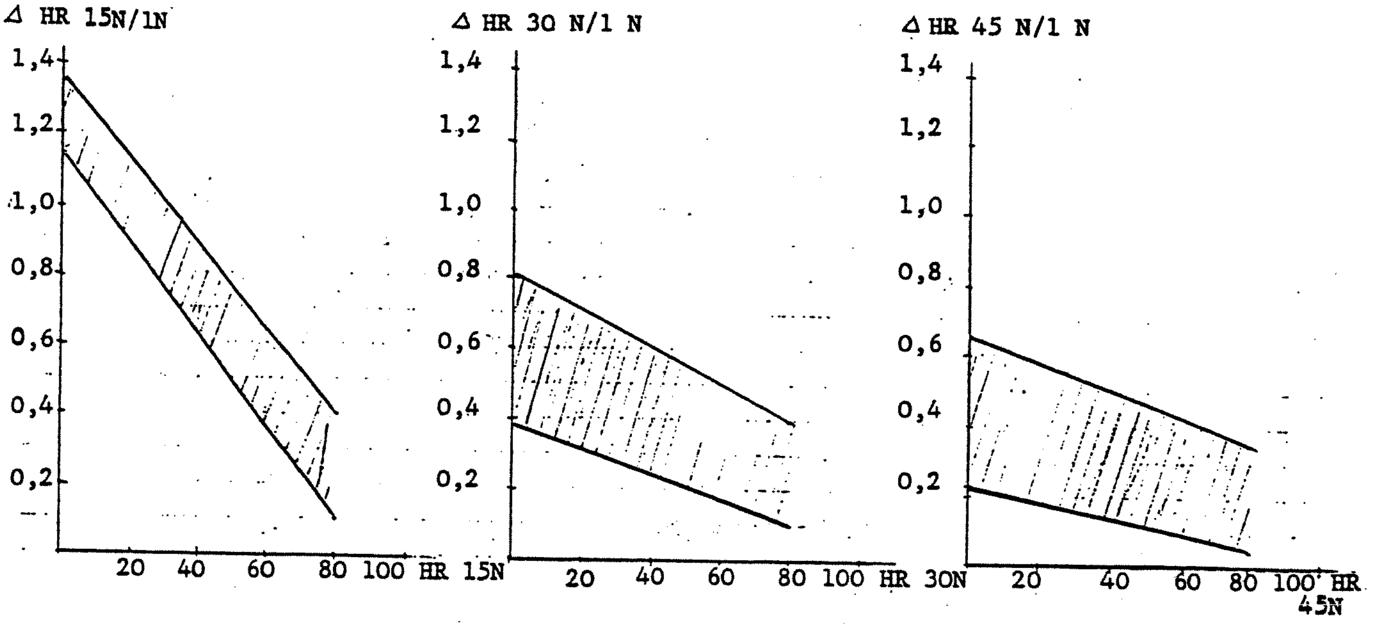


Fig. 2

Error in the HR 15 N, HR 30 N, and HR 45 N hardness values at the effect of an error of 1 N in the preliminary test force F_0, in function of hardness levels.

3.3. Rockwell superficial hardness test (N scale)

The increasing importance of Rockwell superficial hardness tests, especially in the sheet metal industries, is shown by the considerable attention paid to this method especially in Japan. The effect of test force errors on HRN hardness test results, performed by a diamond cone indenter, was examined by YAMASHIRO et al. (Y-10), YOSHIZAWA (Y-15) and KUROKI (K-11). The results of their experiments and calculations, concerning the effect of errors in preliminary test force, can be arranged in the shaded areas in Fig. 2. The three diagrams show the change of apparent hardness at the effect of an increase of preliminary test force F_0 by 1 N, at different hardness levels, for the three possible total test forces, respectively. When examining the effect of errors in total test forces, the results of the three researchers were nearly identical as shown in Fig. 3, again at the effect of increasing the total test force by 1 N.

3.4. Rockwell superficial hardness test (T scale)

The effect of test force errors on HRT hardness test results (performed by a steel ball) was examined by the three researchers mentioned in connection with the HRN scale in point 3.3. and by JEGADEN et al. (J-2). All the published results, obtained theoretically or experimentally, are shown in Figures 4 and 5, in a way completely analogous with the discussion of the HRN scale in the preceding point.

3.5. Brinell and Vickers hardness test

The definition formulae for the Brinell and Vickers hardness test establish a linear relationship between hardness value HB or HV, test force F, and surface area of the indentation A.

$$\text{HB, or HV} = c\,\frac{F}{A} \qquad (8)$$

On the same material F and A change proportionally. Consequently if the test force differs from its nominal value, but its actual value is taken into consideration at calculating the hardness value, no error will arise. If, however, the nominal test force is considered as a constant, and as such included in the c value of the formula, errors of the test force will result in an error of the hardness value, the two errors having an identical percentage value, but opposite sign. For example a test force 0,5% higher than the nominal value will result in an apparent HB, or HV value which is 0,5% lower than the true value. This evident rule was proved also experimentally by LIN ZU-ZEI and YANG DI (L-3) for the Brinell, and by MARRINER (M-3) for the Vickers method. The independence of the HV number from the test force, however, is not valid for low force Vickers hardness tests, because different test forces produce indentations of different depths, penetrating through surface layers of eventually different local hardness, of which only the average value is shown by the indentation hardness test. Experimental data on this phenomenon can be found, among others, in (B-9, W-5, W-13).

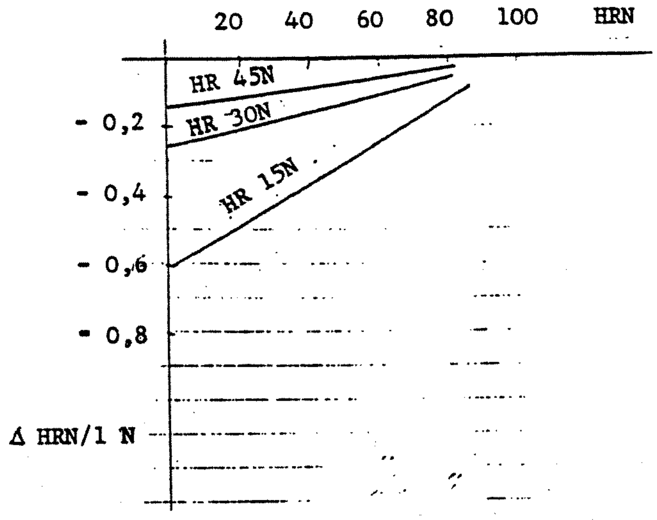


Fig. 3

Error in the Rockwell superficial hardness values (N scale) at the effect of an error of 1 N in the total test force F, in function of hardness levels.

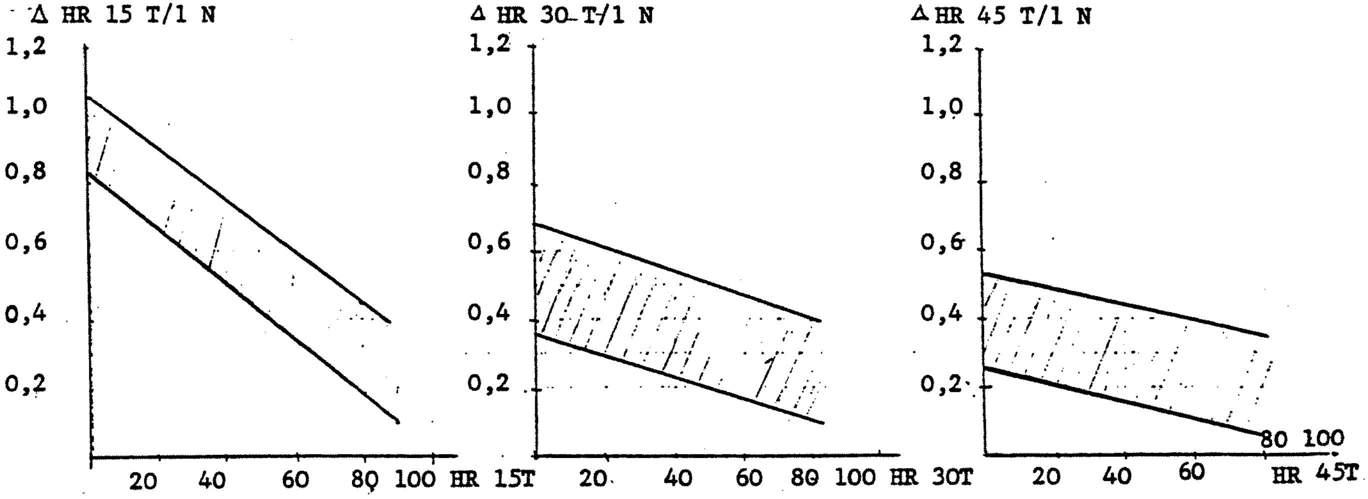


Fig. 4

Error in the HR 15 T, HR 30 T, and HR 45 T hardness values at the effect of an error of 1 N in the preliminary test force F_0, in function of hardness levels.

4. THE LOADING CYCLE

Hardness values are greatly influenced by the velocity and duration of the application of test forces, i.e. by the loading cycle. Therefore the most important values of the cycle are specified in standards.

The loading cycle can be illustrated (R-3) by a dynamic scheme (force vs. time), or by a kynematic scheme (depth of penetration vs. time). In Fig. 6 the two schemes are given for the Vickers and Brinell test (a), and for the Rockwell test (b). The Rockwell scheme is more complicated on account of the preliminary load being applied as the first and last stage of the loading cycle.

A prime consideration in the design of industrial hardness testing machines is that the test shall be carried out in a minimum of time, but without undue loss of accuracy. To achieve a short cycle of operation without introducing impulsive forces, the loading mechanism is usually designed so that the velocity of penetration of the indenter is high in the initial stages, but diminishes to near zero values as the resistance to penetration increases and the penetration is nearly completed. In the majority of machines there is a final stage in the indentation process which occurs when the load controlling mechanism becomes clear of the load before the resistance to penetration is equal to the full load. In such machines the full load is applied a little before the indentation is completed, and penetration continues at a diminishing velocity until static equilibrium is achieved or the load is removed (M-3). In Figure 6 this phenomenon is best illustrated by the difference of times denoted by t_m and t_s , respectively.

The experimental method of plotting the loading cycle was described by RATIU (R-3, R-5, R-6), KHARITONOW (K-5) and WEILER (W-3, W-6). In hardness standardizing machines the loading cycle runs automatically, only some of the parameters are adjustable. In industrial hardness testers the skill of the operator is of great significance. By incorrect manipulation of the machine the cycle can be distorted, as this was shown by YANO-ISHIDA-SHIN (Y-17).

WEILER (W-3) and KRISCH (K-12) described the penetration process mathematically, setting up the corresponding differential equations. The aim of standardizing the loading cycle is to eliminate dynamic effects and to have sufficient time for the stabilization of the penetration process. The prescribed values are summarized in Tables 2, 3 and 4, using the symbols of Figure 6. We see that there are some divergences between prescriptions of different organizations, and even within the same organization the load parameters employed at calibrating the blocks differ from those employed in current hardness tests. The reason for this is that measurements at block calibration are carried out only when time dependent factors have been stabilized, so as to ensure maximum precision. In industrial hardness testing the loading cycle should be carried out as quickly as possible, consequently prescribed parameters were reduced to minimum values ensuring a precision satisfactory for material testing practice.

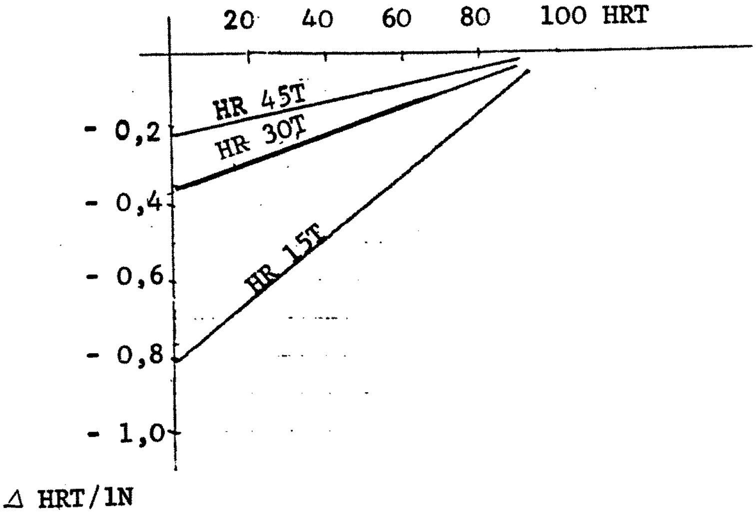


Fig. 5

Error in the Rockwell superficial hardness values (T scale) at the effect of an error of 1 N in the total test force F, in function of hardness levels.

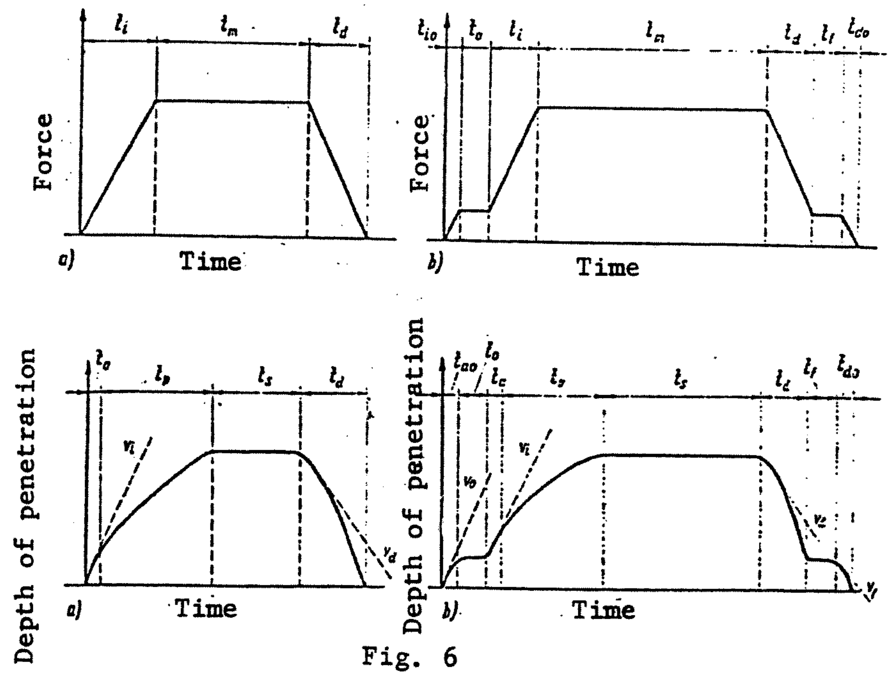


Fig. 6

The loading cycle. Above : Dynamic scheme (force vs. time). Below : kynematic scheme (depth of penetration vs. time)
a) Vickers and Brinell test. b) Rockwell test.

Table 2

Prescribed loading cycle parameters
in various standard specifications.
Rockwell test

	Scope	v (approach) mm/s	v_i µm/s	t_o s	t_i s	$t_a + t_p$ s	t_m s	$t_d + t_f$ s
OIML/IR 11, 12 ISO/R 674 ISO/R 1355	Calibration of blocks	< 1 or	3 - 12	10 - 20			30 - 35	
CMEA/CT SEV 1055	"	< 1		< 15	6 - 8		30 - 35	< 15
ISO/R 80 ISO/DP 6508 ISO/R 1024	Hardness test					2 - 8	2	

Table 3

Prescribed load cycle parameters
in various standard specifications.
Vickers test

	Scope	v (approach) mm/s	v_i µm/s	t_i s	t_m s
OIML/IR 10	Calibration of blocks	< 1 or	3 - 12		
ISO/R 640	"	< 1 or	3 - 12		30 - 35
ISO/DR 640	"	< 1		6 - 8	10 - 15
CMEA/CT SEV 1055	"	< 1		6 - 8	30 - 35
ISO 6507/1 - 1982	Hardness test			2 - 8	10 - 15
ISO 6507/2 - 1982	"			< 10	10 - 15

Table 4

Prescribed load cycle parameters in various standard specifications.

Brinell test

	Scope	v (approach) mm/s	t_i s	t_m s
OIML/IR 9	Calibration of blocks	< 1		
ISO 726 - 1982	"	< 1	6 - 8	10 - 15
CMEA/CT SEV 1055	"	< 1	6 - 8	30 - 35
ISO 6506 - 1981	Hardness test		2 - 8	10 - 15

Experimental values were published on the influence of various elements of the loading cycle (velocities, load application times). These are discussed in the following points.

5. INDENTER VELOCITY

5.1. Rockwell hardness test (C scale)

The approach velocity of the indenter was examined by RATIU and PREXL (R-1, R-3, R-4, R-5, R-6) at the values of 0,2 mm/s, 1 mm/s and 5 mm/s. Significant differences in the measured hardness value were observed only at the extremely high approach velocity of 5 mm/s. They proposed the use of (1 ± 0,2) mm/s what is in conformity with existing prescriptions. According to BARBATO (B-1) indenter velocity during the application of the preliminary test force hardly effects the results.

For the sake of convenience, indenter penetration velocities are often replaced by the duration of load rise time. To obtain conversions between the two values, indentation depth under the preliminary test force and under the additional test force should be known. Assessment of the actual depth of indentation when the preliminary test force is applied is difficult in practice because there is no means of locating the surface of the block in a normal machine. Four methods can be employed to overcome this difficulty :

a) Measurement of the diameter of the indentation produced by the preliminary test force on a highly polished surface.

b) Assumption that surface areas of indentations are equal for the HRC indenter and for the HV indenter under the same preliminary test force of 9,81 N.

c) Assumption that the surface area of the indentation under the total test force is fifteen times greater than that under the preliminary test force or, in other words, that the surface area is proportional to the load.

d) Calculation of indentation depth for a HB indenter of 0,4 mm diameter under a force of 9,81 N, by adding an estimate for the elastic recovery of the material. This method is applicable because mostly only the spherical part of the HRC indenter contacts the material at the preliminary test force.

The values measured or calculated by BOCHMANN and HILD (B-5), YAMAMOTO and YANO (Y-5), WOOD, ANTHONY and COTTER (W-22) can be arranged in the shaded zone of Figure 7.

The increase in depth of indentation under the additional test force can be read on the hardness tester, after the depth measuring instrument had been set to zero at the preliminary test force. The values measured or calculated by WEILER (W-3), YAMAMOTO and YANO (Y-5), and WOOD et al. (W-22)

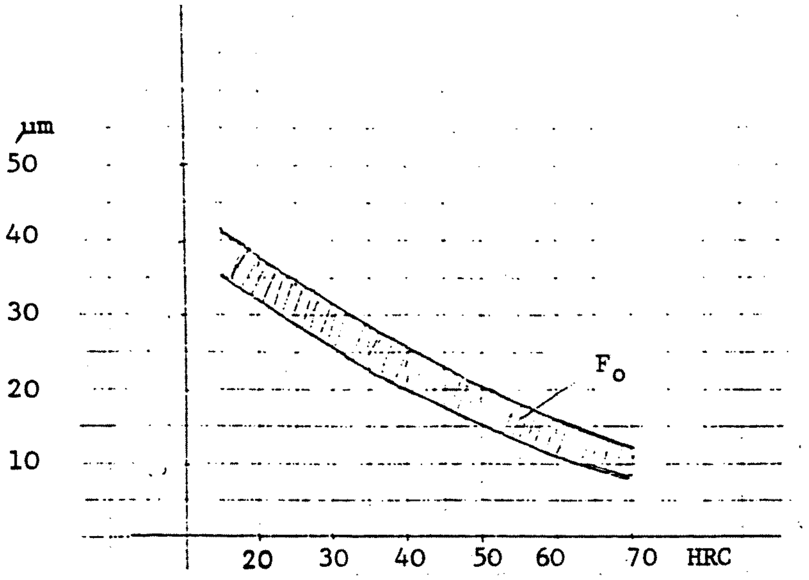


Fig. 7

Depth of HRC indentation under the preliminary test force before application of additional test force, in function of hardness level.

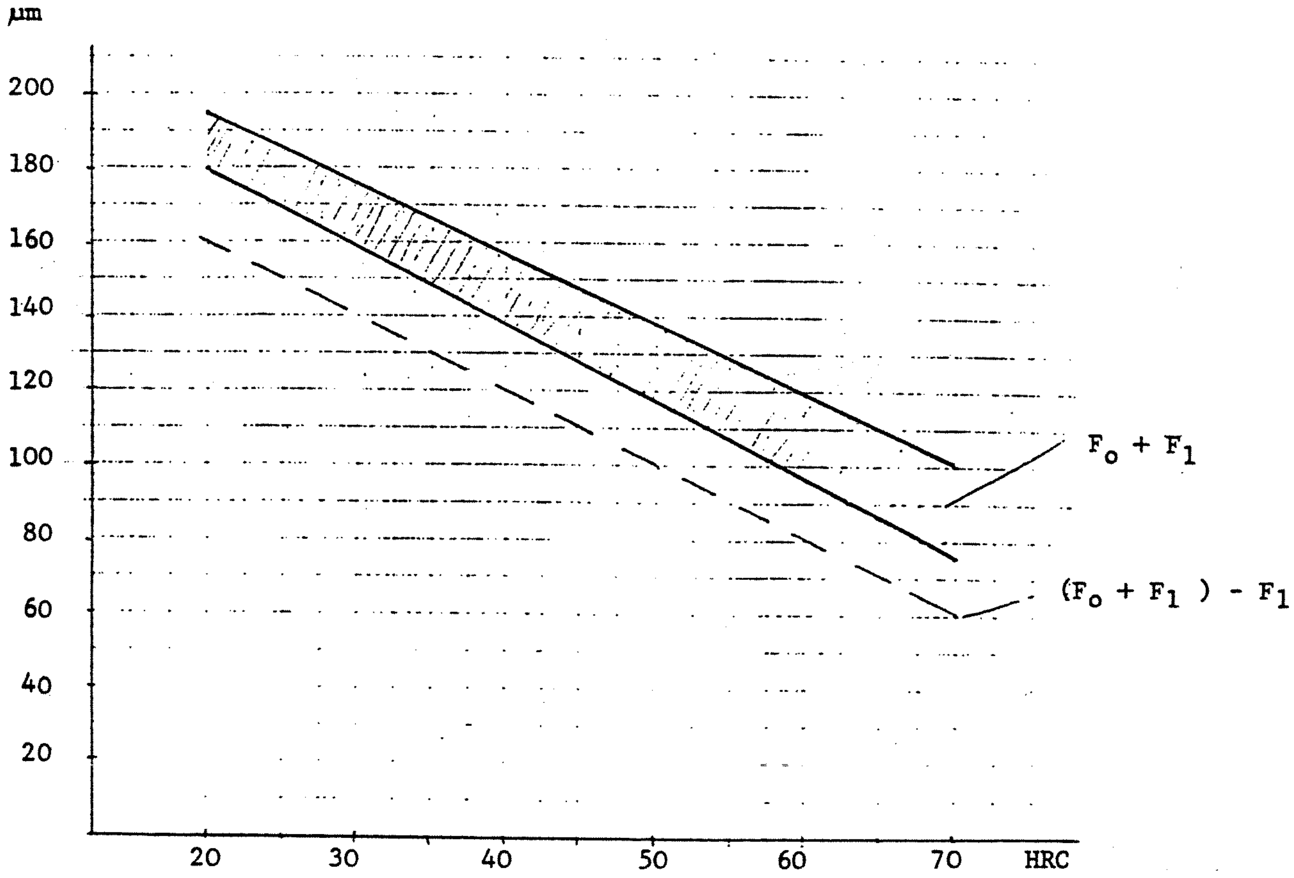


Fig. 8

Increase in depth of indentation under additional test force (marked by $F_o + F_1$) and permanent increase of depth of indentation under preliminary test force after removal of additional test force (marked by $(F_o + F_1) - F_1$), in function of hardness level.

are shown by the shaded zone in Figure 8. For comparison purposes the permanent increase of depth of indentation under preliminary test force after the removal of the additional test force is also marked in the Figure (dotted line). This latter is actually the function defining Rockwell hardness. The difference between the shaded zone and the dotted line is the elastic recovery of the specimen at the removal of the additional test force.

After having examined the depth of indentation under the test forces F_o and $(F_o + F_1)$, respectively, the effects of the velocity of penetration can be examined. YAMAMOTO and YANO (Y-5, Y-6) examined the change of hardness in function of the velocity of penetration. The results are shown in Figure 9. Greater velocity means lower apparent hardness, and this effect is greater at higher hardness values. It should be recalled that the range of velocities given in international prescriptions (see Table 2) is 3 - 12 µm/s what corresponds only to the right side third part of Figure 9. In this range hardness changes are below 0,1 HRC.

The values measured by WEILER (W-3) were approximately the half of those shown in Figure 9, with no significant effect at all below 40 HRC. Figure 10 shows the results obtained by MARRINER (M-4, M-6) on a block of high hardness (67 HRC). This experiment included also very low penetration speeds where the apparent increase of hardness is considerable. In the velocity range of the standard specifications the change of hardness was of the order of 0,2 HRC, the double of the value given in Figure 9. It will be seen from these results that hardness values obtained on a standardizing machine may become undeterminate unless the specified indenter velocity is maintained.

Experimental values of BARBATO (B-1) coincide with those of Marriner. HORMUTH (H-7) and SLAVINA (S-4) made their measurements at load rise times of 6 - 24 s. A significant effect on the hardness value was observed only at low hardness levels (25 HRC), where the above-mentioned times correspond to approximately 7 - 28 µm/s velocity.

KRISCH (K-12) examined this effect on industrial hardness testers both theoretically and experimentally. The conclusion was that penetration velocity should not be higher than 0,1 mm/s in any case. ISO/R 80 specifies a time range of 2 - 8 s for load increase on industrial Rockwell testers. It can be simply checked that even at low hardness levels the lowest time specified, i.e. 2 s, corresponds to a penetration velocity of below 0,1 mm/s.

5.2. Vickers hardness test

SLAVINA (S-4, S-12) and RATIU (R-5, R-6) examined Vickers hardness with approach velocities of 0,2, 1, and 5 mm/s. Higher velocity resulted in a greater indentation i.e. lower hardness, but this effect was found to be significant statistically only at 5 mm/s.

A number of experiments were made by MARRINER (M-3), in which groups of ten indentations were made on a block under identical conditions, except that the uniform velocity of loading was changed. Typical results on two blocks of hardness 950 HV and 500 HV are shown in Figures 11 and 12. It

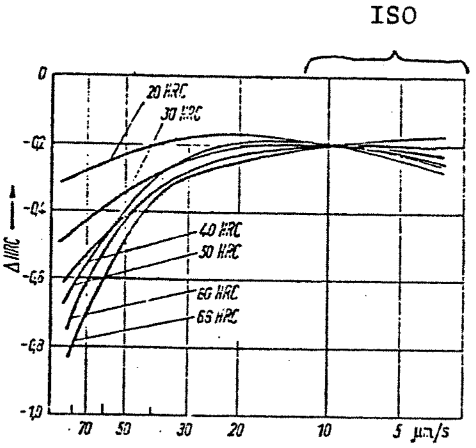


Fig. 9
Change of HRC hardness in function of the velocity of penetration, at different hardness levels.

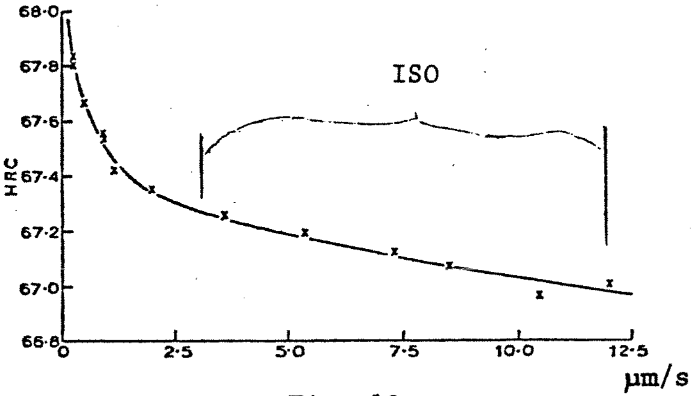


Fig. 10

Hardness values of the same HRC block measured with different velocities of penetration.

will be seen from these results that as the velocity of penetration is decreased the hardness value increases, and in particular the rate of increase is greatest as near-zero velocities are attained. The range of velocities prescribed in standards (3 - 12 µm/s) is marked in the figures. The curve has a considerable slope even within this range.

WEILER (W-7) made an experiment on industrial hardness testers at load rise times between 1 and 120 s. The effect on the measured hardness value was, of course, dependent on the hardness level, but significant effects were noticed only at load rise time values below 5 s. KRISCH (K-9) found no inertia effects on dead-weight load hardness testing machines even in the case of load rise times shorter than those specified in standards (6-8 s). His dynamical examinations confirmed the correctness of the range of 2 - 8 s specified for industrial hardness testers.

5.3. Brinell hardness test

The examination of the effect of different approach velocities by RATIU (R-6) resulted in a conclusion different from those at the Rockwell and Vickers test. In the case of Brinell tests the direction of the effect is inversed by changing the test load, as follows :

HB 2,5/187,5 : Higher velocity results in lower apparent hardness,
HB 5/750 : Effect not significant,
HB 10/3000 : Higher velocity results in higher apparent hardness.

These effects are especially pronounced at low hardness levels. The Brinell test involves greater test loads and results in larger indentations than the other two examined methods. Accordingly dynamic effects have a greater influence on measurement results. KRISCH (K-9, K-12) examined the inertia forces which may alter the test load. For different ball diameters and test loads those load rise time and indentation velocity values were determined by calculation, at which test loads are falsified by 0,5%. This effect is higher at performing a Brinell test, than in the case of Vickers or Rockwell tests. LIN ZU-ZEI and YANG DI (L-3) found hardness changes going up to 0,5% in the range of 100 - 200 HB, if the approach velocity was changed from 0,1 to 0,6 mm/s.

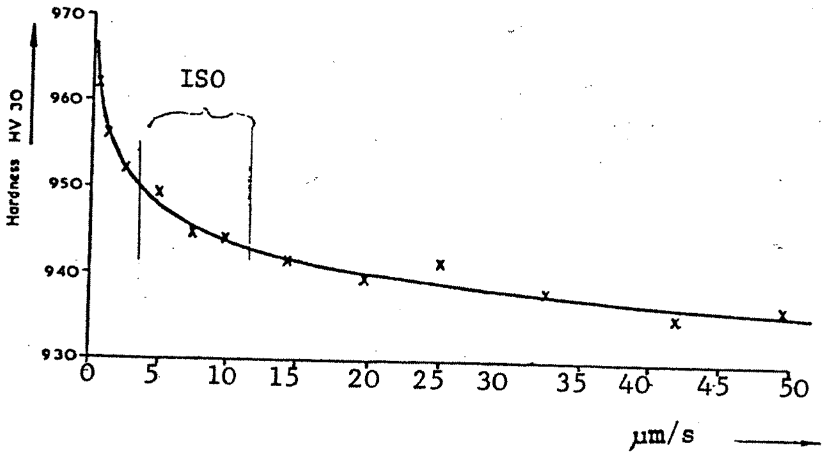


Fig. 11

Hardness values of the same HV 30 block measured with different velocities of penetration.

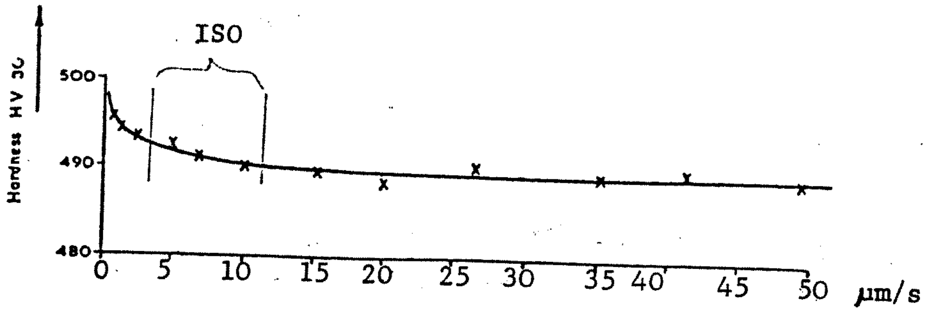


Fig. 12

Hardness values of the same HV 30 block measured with different velocities of penetration.

6. LOAD APPLICATION TIME

6.1. Rockwell hardness test (C scale)

Significant changes in hardness value are obtained if the duration of test force is varied. This is due to creep. Longer load application means deeper penetration, i.e. lower apparent hardness. This effect is more pronounced at low hardness levels as shown by the experimental results of YAMAMOTO (Y-5) in Figure 13. Differences in measured hardness are given with respect to the value obtained with a load application time of 10 s. By considering the t_m values specified in standards for hardness tests and block calibrations differently (see Table 2), we may have a shift of the nominal value of the block of about 0,3 HRC for high and as much as 1 HRC for low hardness levels. This difference in specified load application times is the result of differing requirements. Metrology laboratories want to have a stabilized hardness, where the curves in Figure 13 run nearly parallel to the time axis. In material testing practice time is pressing, tests should be made rapidly.

ROSSOW (R-13) recognized that hardness changes in a logarithmic function of load application time,

$$\mathrm{HRC} = a - b \log t, \qquad (9)$$

where t denotes time, while a and b are constant for a given hardness level. Figures 14, 15 and 16 show his results as a straight line, if a logarithmic time scale is employed.

Similar experiments were made by several research workers. The measured values of HORMUTH (H-7), PILIPTCHUK (P-15), RATIU (R-4, R-6), WEILER (W-3, W-12), YAMAMOTO (Y-5) and YAMASHIRO (quoted in Y-13) can be arranged in the shaded zones along the line given by ROSSOW in Figures 14, 15 and 16, constructed for the hardness levels 20-25, 45-50 and 60-65 HRC, respectively.

In the case of soft materials flow may continue for longer application times too, which are however of no practical importance. PHILLIPS and FENNER (P-13) mentions the case of a block which was measured 28,0 HRC after 2 minutes, and 26,9 HRC after 15 minutes of load application. This value could still be arranged in the shaded zone of Figure 14 if the diagram were accordingly extended.

6.2. Vickers hardness test

The results obtained with various load application times for two blocks of hardness 220 HV and 875 HV by MARRINER (M-3) are shown in Figures 17 and 18, respectively. Similar examinations were made also by BURMAKINA et al. (B-6), RATIU (R-6) and SLAVINA (S-4, S-12). Their results obtained at similar hardness levels can be arranged in the shaded zone around the curves of Figures 17 and 18.

It will be seen from these results that for high hardness the curve rises appreciably for durations less than 20 seconds, but for durations between 30 and 100 seconds, although static equilibrium may not have been attained, the change of hardness value is in the neighbourhood of only 1 HV. Such results indicate that for hard specimens the duration of load application

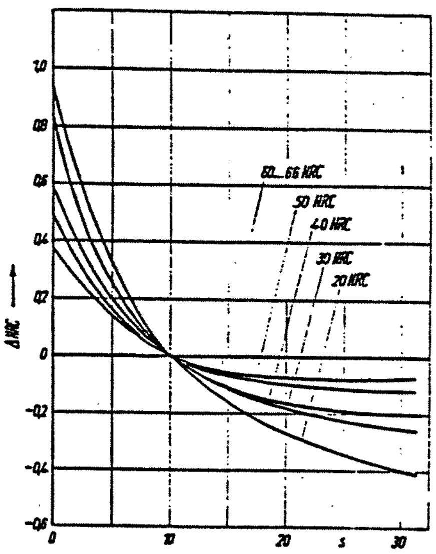


Figure 13

Change of HRC hardness in function of load application time, at different hardness levels.

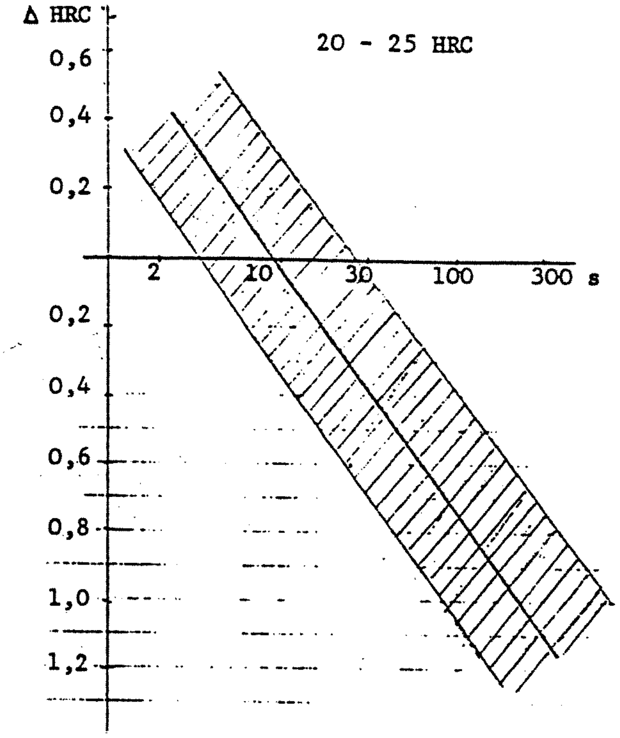


Figure 14

Change of HRC hardness of soft blocks in function of load application time.

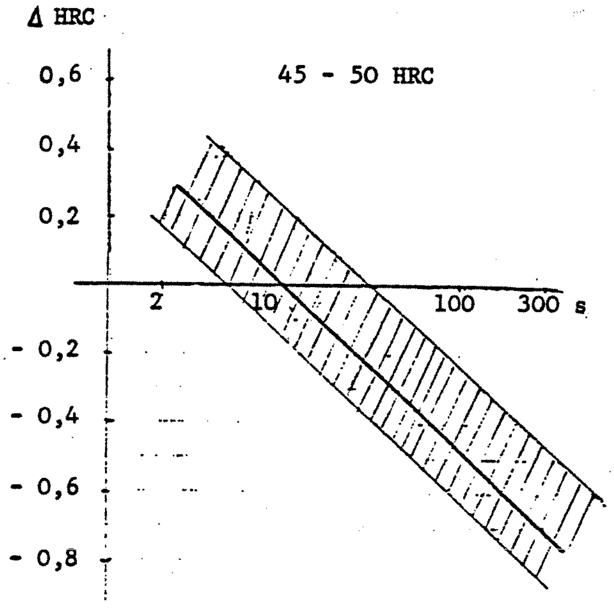


Figure 15

Change of HRC hardness of medium level blocks in function of load application time.

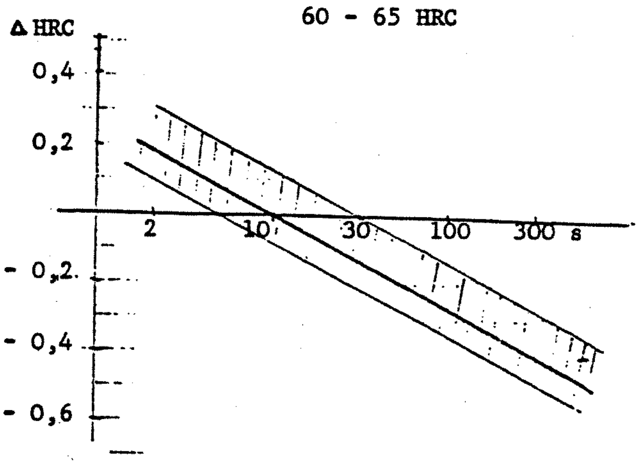


Figure 16

Change of HRC hardness of high hardness blocks in function of load application time.

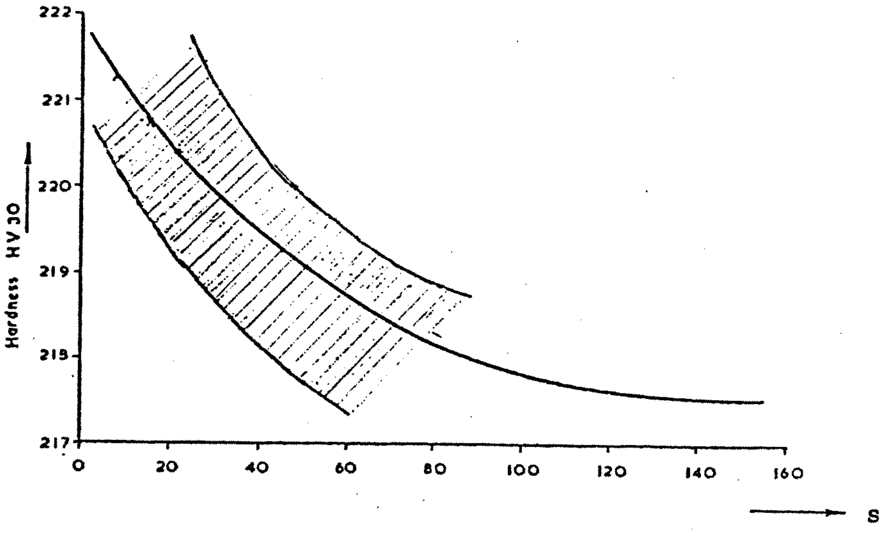


Figure 17

Hardness values of the same HV 30 block measured with different load application times.

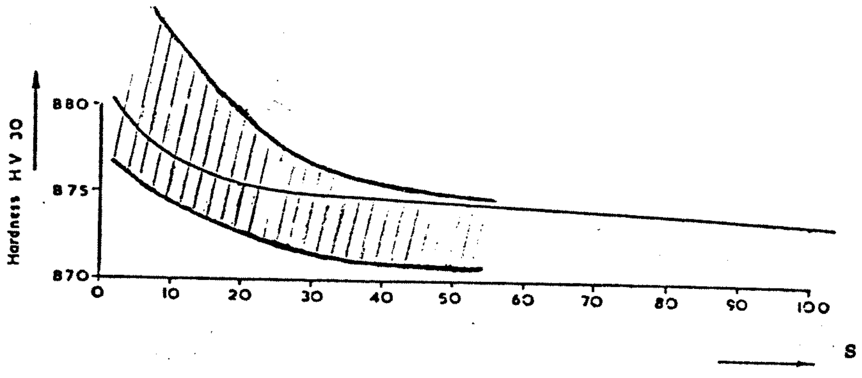


Figure 18

Hardness values of the same HV 30 block measured with different load application times.

of 30 s is appropriate. However, Fig. 17 shows that for a soft test block, static equilibrium is not achieved for at least 2 minutes after the application of the test load. But even for calibration work this would be an excessively long time, from both an economic point of view and the difficulty of ensuring complete freedom from external vibration. 30 s seems to be the reasonable compromise between divergent factors.

6.3. Brinell hardness test

Load application time may be important in the case of Brinell hardness tests, generally used for softer materials. Some early experimental results on different materials are quoted in (W-13). LIN ZU-ZEI (L-3) obtained the results shown in Figure 19 on steel standardized blocks. RATIU (R-6) examined the difference of the results of Brinell tests performed with load application times of 15 and 30 s, respectively, but the difference was found to be not significant statistically (at the 95% probability level).

The experimental results underline the necessity of strictly keeping the values prescribed in the standards (Table 4), especially at low hardness levels.

7. TEMPERATURE

Hardness test blocks are standardized generally at stable laboratory temperatures, approximately at 20 °C. In industrial hardness tests, however, especially in the workshop, temperatures differing from that employed in the standardizing laboratory may occur. Therefore the knowledge of the temperature coefficient is useful.

The experimental equipment, a thermostat built on the hardness standardizing machine, was described by KERSTEN (K-1). Temperature coefficient values for the HRC test were published by two research workers. Both found negative values, i.e. higher temperature results in lower hardness. YAMAMOTO and YANO (Y-5, Y-6) found a correlation between the temperature coefficient and the hardness level for Japanese blocks, as follows :

- 0,01 HRC/°C	at	60 HRC
- 0,02 HRC/°C	at	40 HRC
- 0,03 HRC/°C	at	20 HRC

(see lines denoted by Y on Figure 20).

KERSTEN (K-1) found a temperature coefficient of 0,0185 HRC/°C, independently of the hardness level. Values obtained on different blocks can be arranged in the shaded zone of ± 0,1 HRC width around the line marked by K in Figure 20. Both authors emphasize that their values are valid only for blocks produced in their respective countries. But the data presented in Figure 20 coincide fairly well.

For the Vickers hardness KERSTEN obtained a temperature coefficient of - 0,0525%/°C. The corresponding change of hardness at a temperature difference of 20° is illustrated in Figure 21 in function of nominal hardness determined at 21 °C. The regression line is shown with a shaded uncertainty zone corresponding to ± 1 μm diagonal length. (Measurements were made with a load of 980,7 N, in the temperature range of 1 - 43 °C.)

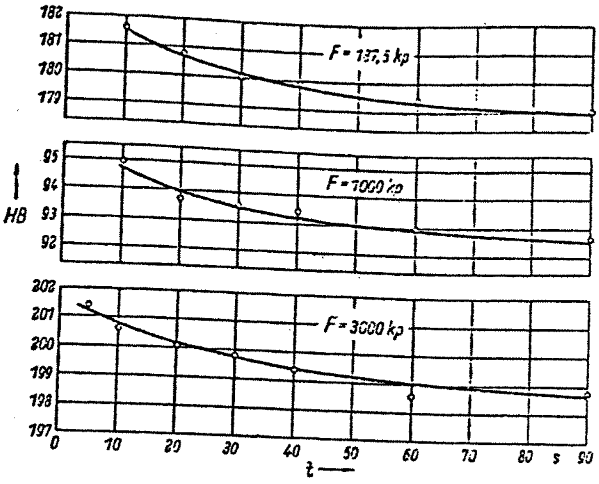


Figure 19

Hardness values of three HB blocks measured with different load application times and test forces.

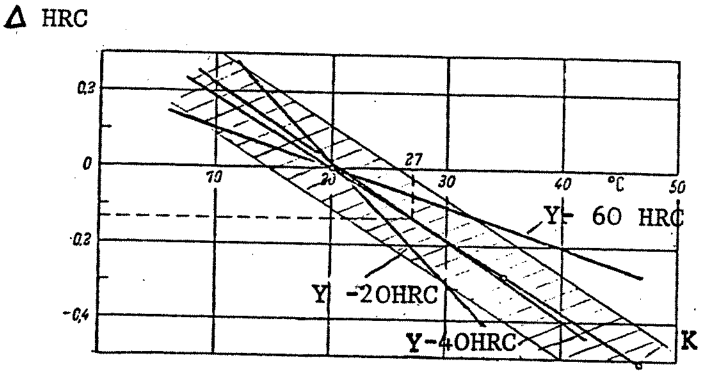


Figure 20

Errors in HRC hardness at the effect of temperature changes.

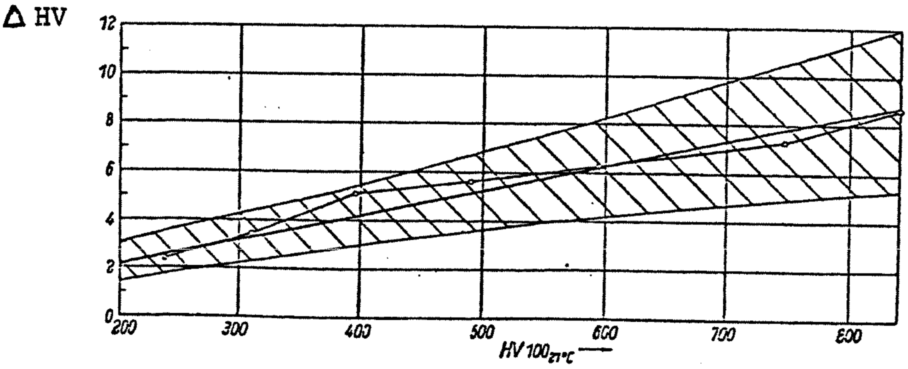


Figure 21

Errors in HV hardness at the effect of a temperature change of 20 °C, in function of hardness level.

8. THE INDENTER

The indenter is the element of the measuring equipment which is in direct contact with the material to be measured. It is producing the indentation the dimensions of which actually characterize hardness, consequently deviations of the indenter from prescribed values have decisive influence on measurement results.

It is well known in hardness testing practice that it is difficult to achieve agreement between several machines over the whole range of hardness values if more than one indenter is involved. The necessity for supplying indenters for standards purposes, which give identical performances in any standard machine, is acute.

Influence factors are fairly different in the case of diamond cones or pyramides, and of steel balls, accordingly they are discussed separately.

8.1. Diamond cone

Because the angle of the cone and radius of the tip are important and relatively easy to measure, and specifications give tolerances for them, a number of research workers have established correlations between angle or radius error and performance. However, little attention has been given to the requirements that the indenter shall be a right circular cone or that the spherical tip shall blend tangentially with the cone, and no specification has attempted to assign tolerances to these features. This may have to be remedied in future.

The effect of different geometrical errors is different at each level of hardness. Let us take a simple example. Figure 22 shows the possible deviations of tip radius and of included angle. Both have a direct effect on measured hardness value. A radius or cone angle higher than nominal value, namely, impede normal penetration into the specimen, consequently apparent hardness is generally higher. (Practical experience may produce cases contrary to this evident explanation, as it will be shown later in point 8.1.2).

At Rockwell C, A and N tests first the spherical part of the indenter contacts the material, similarly as in the case of an imaginary Brinell test with a 0,4 mm diameter ball. After having reached a penetration depth of 27 µm, the conical part of the indenter also participates in indenting the specimen. According to the testing method and the hardness of the specimen, three cases are possible (W-13) :

a) Both under preliminary and total test force only the spherical part of the indenter is active;

b) Under preliminary test force the spherical, under total test force also the conical part is active;

c) Both under preliminary and total test force also the conical part of the indenter is active. In the case of the Rockwell C method case a) occurs only theoretically, for hardness values above 87 HRC. All practically occuring HRC values are produced under conditions of case b). In turn, HRN 15 measurements are carried out almost always according to case a). The relation of the effects of the two parts of the indenter is different

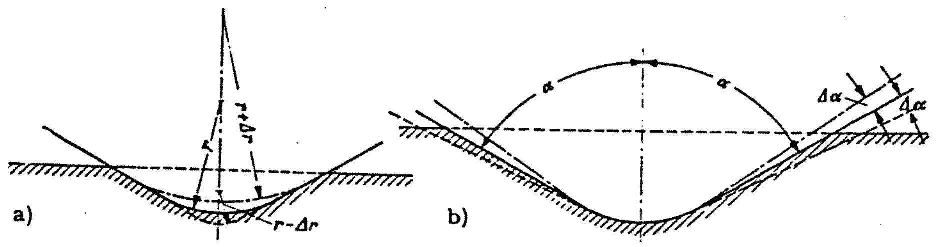


Figure 22

Possible deviations in the geometry of a HRC indenter :

a) Tip radius, $r \pm \Delta r$
b) Included angle, $\alpha \pm \Delta \alpha$

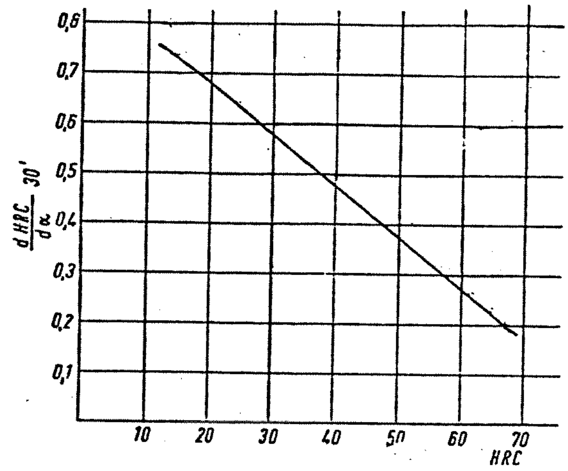


Figure 23

Error in HRC hardness values at the effect of an error of 30 ' in the included angle of the penetrator, in function of hardness level.

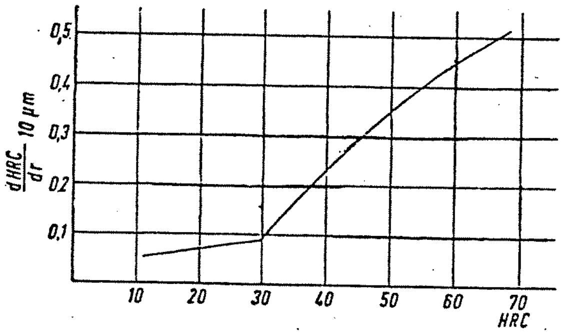


Figure 24

Error in HRC hardness values at the effect of an error of 10 μm, in the tip radius of the penetrator, in function of hardness level.

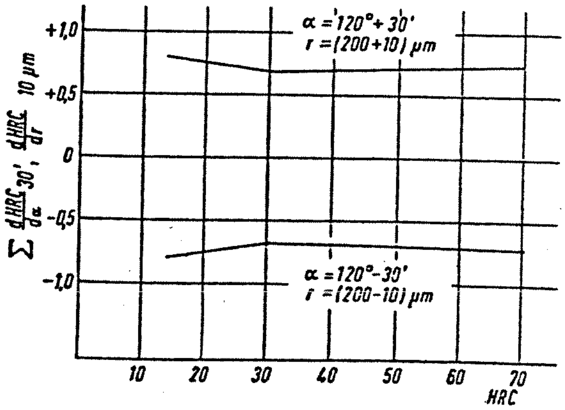


Figure 25

Error in HRC hardness values at the combined effect of included angle and tip radius errors shown in Fig. 23 and 24.

for different test forces and specimen hardness values. For low forces and high hardness, the effect of the spherical part is greater in relation to that of the cone, the role of which is growing with lower hardness or higher test forces. The effect of poor blending between sphere and cone may be very important if either under preliminary or total test force penetration depth is around 27 µm (zone of blending).

Because different form deviations interact, and no one of them could be observed alone on an otherwise perfect indenter, the precise effect of each is not easy to determine experimentally.

8.1.1. Angle and radius errors

Several workers tried to determine the effect of angle and radius error by calculation. The calculation method of BOCHMANN and HILD (B-5) is based on the following assumptions : In the case of identical hardness the surfaces of indentations made by different indenters are equal. The shape of the identation is identical with that of the indenter. The wall formed at the edge of indentation does not influence the magnitude of contact surface. These assumptions are of course only partially true. The results of calculation are shown in Figure 23 for an angle error of 30' and Figure 24 for a radius error of 0,01 mm, respectively. The cumulated effect of the two errors is shown in Figure 25, indicating that the error limits specified in the standards may result in an error of measured hardness in the range of ± 0,7 HRC. It should be emphasized that this error arises in the case of perfect blending of the spherical and conical part and of an otherwise perfect indenter. The experimental verification of the method is made difficult by the fact that several influence factors are to be separated (H-4, H-6).

The method of calculating corrections (H-4) was further examined and developed by BARBATO (B-3) both experimentally and theoretically. Corrections were calculated on assuming identical contact surfaces, identical indentation volumes, and identical projected areas for the examined indenter and for the indenter having nominal dimensions. Several researchers tried to establish the effect of angle and radius errors experimentally. PHILLIPS and FENNER (P-13), using indenters with angles within actually employed tolerances, did not find a statistically significant effect. Radius errors had a significant effect only above 45 HRC. A tentative theoretical formula was also established, being in fair correlation with experimental results.

Rockwell C indenters made of hardened steel and hard metal were used in the experiments of STEPANOW (S-9). These materials could better be ground and polished to predetermined angles and radii. By evaluating the mean of the results of his own experiments and of those of two other researchers, he found the effect of angle and radius error on Rockwell C hardness to be :

$$\frac{d\,H}{d\alpha} = 1{,}446 + (1 - 2{,}38\ H)\ H.10^{-4} \qquad (10)$$

and

$$\frac{d\,H}{d\,r} = 1{,}62\ .10^{-2} - 0{,}75\ (1 - 0{,}1\ H)\ H.10^{-4} \qquad (11)$$

where H is measured hardness in HRC, $d\alpha$ angle error in degrees, and $d\,r$ radius error in μm.

In this experiment the effect of the curvature of the generatrix of the cone has also been determined. This is an influence factor often producing surprising effects.

The statistical evaluation of the form errors on 36 Rockwell diamond indenters by ROSSOW (R-11) produced results fairly coinciding with those of other experiments. The possible combinations of angle and radius errors may result in noteworthy conclusions (Figure 26). The two errors may have identical or opposite signs. Measurement results for various indenters, all being at the limit of the tolerance range are shown in the figure. If the two errors have identical sign (identers A and D), the resultant error is relatively large (nearly 1 HRC), but not changing too much in the practically used hardness range. If we employ a general correction value of 0,8 HRC for these indenters, the effect of the two errors will be practically eliminated in the whole range of Rockwell C hardness. In the case of indenters B and C, however, for which the errors have opposite signs, the necessary correction is about + 0,5 HRC at the one end of the hardness scale, and - 0,5 HRC at the other, i.e. a change of the necessary correction in the order of 1 HRC. Since, on account of costs, it is not sure that indenter corrections are determined in function of hardness, especially in the case of indenters used in industry, it may happen that a functional examination performed at a single, medium hardness value leads to the conclusion that no correction is necessary. When measuring at both extremities of the HRC scale, erroneous results may be obtained. Consequently, if there is a possibility of choice, indenters with geometrical errors in the same direction, used with a general correction, are preferable. In the tests of ROSSOW, the uncertainty of radius measurement was ± 0,01 mm, while that of angle measurement ± 6'. The former value is not sufficient since it results in an uncertainty of hardness exceeding usual standard deviations of good quality hardness testers. The indicated uncertainty of angle measurement is satisfactory for the given purpose.

WOOD, COTTER and NASH (W-21) published the results of the evaluation of the performance of 20 indenters from five different producers. The relationship between the radius of the spherical tip and the Rockwell hardness value was found to be 0,50 HRC/0,01 mm at 27 HRC, 0,62 HRC/0,01 mm at 46 HRC, and 0,59 HRC/0,01 mm at 60 HRC. These values lie higher than the zone given in Figure 27.

The influence of tip curvature was determined by YAMASHIRO and UEMURA (Y-9) using an indenter having a radius of 0,15 mm originally. After having performed hardness measurements, the indenter tip was reground to 0,167 mm and hardness measurements repeated. This gradual increasing of radius was continued in 7 steps up to 0,25 mm. The correct shape was always checked after grinding by taking interference pictures. A linear correlation between radius error and hardness error was established. The correlation coefficient was 0,90 at 68 HRC, gradually decreasing to 0,59 at 30 HRC, where the effect of the radius is of less importance. The error can be expressed by the formula :

$$\frac{d\,H}{d\,r} = 6{,}58.10^{-2} - 0{,}88\,(100 - H)^2 \,.\, 10^{-5}\,, \qquad (12)$$

where H is measured hardness in HRC, and d r radius error in μm.

In the same series of experiments, to determine angle error effects, 30 selected indenters with different cone angles in the range 120 ° ± 20' were used. Measured hardness values were corrected to account for radius errors according to formula (12). The linear correlation between angle error and hardness error is characterised by a correlation coefficient of 0,45 at 68 HRC, increasing gradually to 0,86 at the hardness level 30 HRC, where the role of the conical part of the indenter is preponderant. Angle error can be expressed by the formula :

$$\frac{d\,H}{d\alpha} = -\,0{,}496 + 2{,}72.10^{-2}\,(100 - H) \qquad (13)$$

where $d\alpha$ is angle error in degrees.

To <u>summarize</u> the results of calculations and experiments to establish the effect of cone angle and tip radius errors of the Rockwell C indenter, the shaded zones in Figure 27 include all the results mentioned in this chapter (with the exception of (W-21)), as well as those of MIKOSZEWSKI and BOLESLAWSKA (M-19). Errors are given in function of the hardness level, for the tolerance values specified in standards, namely ± 30' for angle and ± 0,01 mm for radius. The values obtained by different methods coincide fairly well. These figures support the simple rule formulated by K. YAMAMOTO and YANO (Y-6) according to which in the case where there is no suitable inspection method for the form of an indenter, the uncertainty of hardness standard originating from form errors must be accounted for by as much as ± 1 HRC. This same value is specified in international recommendations (SR-11, SR-24) as the permitted maximum error for the Rockwell C indenter.

Rockwell N Scale

The effect of geometry errors of diamond cone indenters for hardness measurements on the Rockwell (superficial) N scale was examined by YAMASHIRO et al. (Y-10), YOSHIZAWA (Y-15) and KUROKI (K-11). Values determined by different authors experimentally and by calculation do not coincide to such a degree as in the case of the HRC scale. In the ranges of measurement recommended for use in (SR-2) the effect of a radius error of 0,01 mm was found by different authors to be :

0,3 - 1 HR 15 N
0,5 - 1 HR 30 N
0,6 - 1,2 HR 45 N

without a clear correlation between hardness and the magnitude of the error. Differences are attributable to differences in the methods of determination.

As to the angle error, a correlation similar to that established for HRC measurements was found : Angle error has an increasing effect as hardness

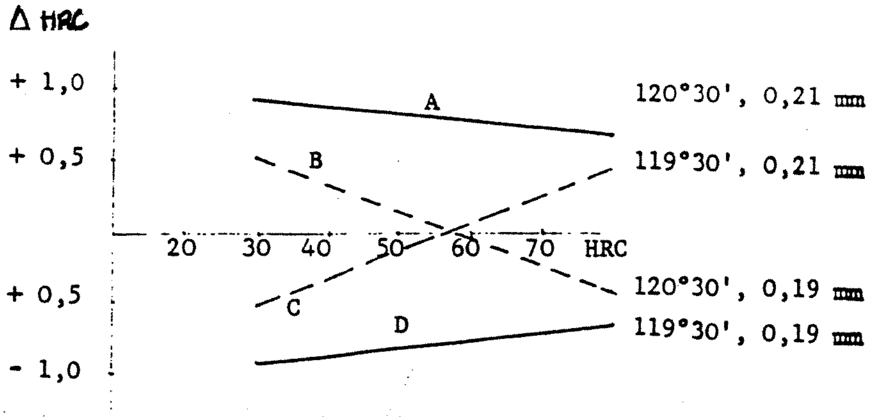


Figure 26
Possible combinations of included angle and tip radius errors on HRC indenters.

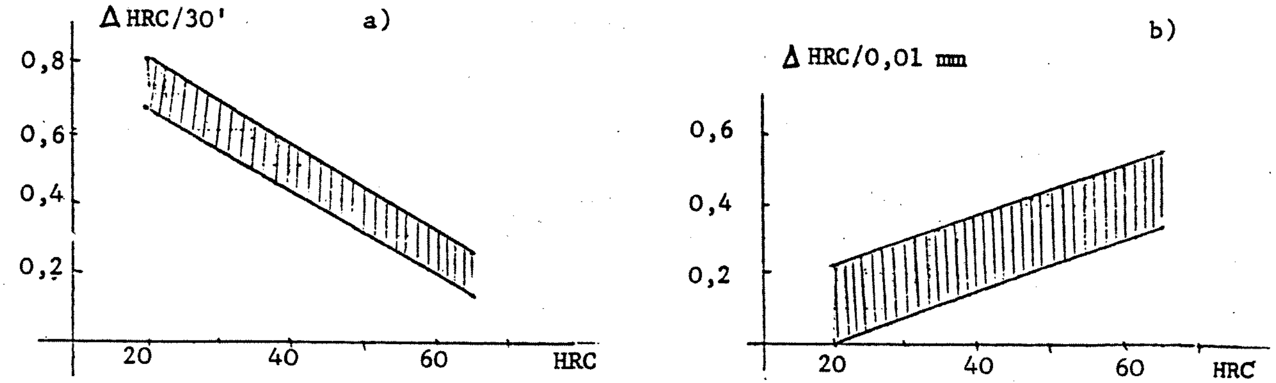


Figure 27

Error in the HRC hardness value at the effect of an error of 30 ' in the included angle (a), and of 0,01 mm in the tip radius, respectively, in function of hardness level.

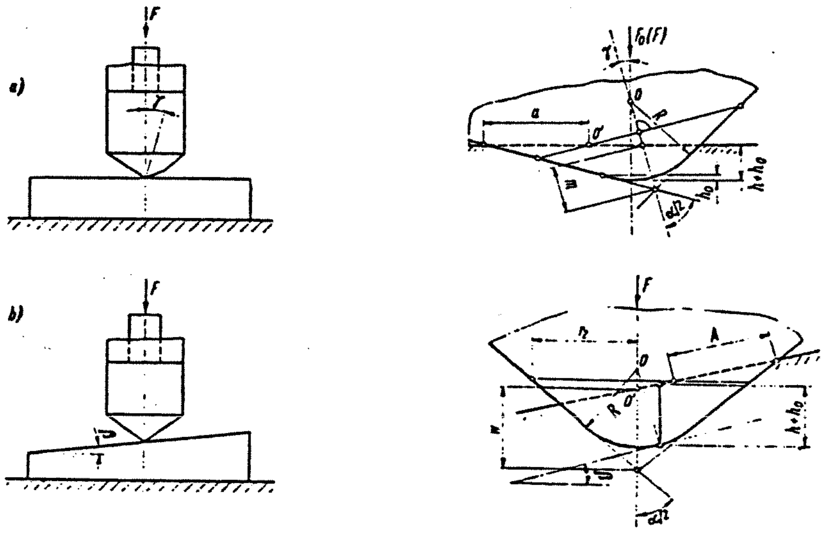


Figure 28
Inclination of the indenter :
a) Included angle between the axis of the diamond cone and that of the indenter
b) Axis of the indenter not perpendicular to the tested surface.

decreases. For an angle error of 0,5°, hardness errors of up to 0,8 HR 15 N, HR 30 N, HR 45 N were found.

8.1.2. Other form errors

Investigations into the form and performance of conical diamond indenters (N-1) have shown that, while errors in cone angle and radius of the spherical tip are precisely correlated with changes in hardness value, the effect of lobing is more difficult to assess. The effect of form errors other than those of the angle and radius can be given only qualitatively, indicating the probable direction of change in hardness value. It has been observed that three-lobed indenters give progressively lower values towards the soft end of the scale and considerable errors in tip form and angle are required to compensate this effect. Although a precise correlation between these errors of form and their effect is not yet available, Table 5 gives the direction and relative magnitude of the error in hardness value introduced by each type of error in the form, at each stage of the indentation process, together with the cumulative effect on performance (M-8). (+ and ++ in the Table denote effects producing higher hardness values, - and -- effects lowering measured hardness values, while 0 stands for no effect). This table is useful in predicting the performance of an indenter or locating an additional fault if the performance is known. For example, an indenter with a large radius will give high values on a hard block, and slightly high values on a soft block unless there is some compensating defect, such as a three-lobed cross section which will lower the hardness values, particularly on a soft block. In addition it explains why two indenters which show reasonable agreement on one set of test blocks covering the complete range of hardness can show a large divergence at particular levels on a second set of blocks. For example, if one indenter has a slightly flat tip and the second set of blocks have a different surface hardness from the first, then the indenters will behave quite differently in stage 1 on particular blocks whilst behaving consistently at stages 2 and 3.

Indenters satisfying all the requirements for a standard as regards macro-geometry and surface finish can produce hardness values deviating by ± 1 HRC (M-11). This is due to micro-geometrical differences.

Experiments trying to establish a correlation between surface finish and penetration depth (W-14, W-12) were inconclusive, therefore some data were not even published.

8.2. Diamond pyramid

The effect of an error in the angle between opposite faces of the Vickers indenter (tolerance ISO 146 : 136 ± 0,5°) was examined by WEINGRABER (W-13) and WOOD et al. (W-22). The error in hardness was found to be :

Table 5

EFFECT OF ERRORS OF FORM ON PERFORMANCE

(according to MARRINER and WOOD (M-8))

Test block	Error of form	Stage 1 Preliminary load	Stage 2 Total load	Stage 3 After removal of additional load	Effect on hardness value
Hard	Large radius	– –	+ +	+ +	+ +
	Large angle	0	+	0	+
	Three lobes	0	–	0	–
	Flat at tip	– –	0	+	–
	Sharp tip	+ +	0	–	+
Soft	Large radius	–	+	+	+
	Large angle	0	+ +	0	+ +
	Three lobes	0	– –	0	– –
	Flat at tip	0	0	0	0
	Sharp tip	0	0	0	0

$$\Delta \mathrm{HV} = \frac{\sin 68^\circ}{\sin \phi/2} - 1 \qquad (14)$$

where ϕ is the actual angle between the opposite faces of the indenter. If ϕ is smaller than nominal, the measured hardness will be higher and vice-versa. At the limits of the tolerance field specified in ISO 146 (± 0,5°) the error in hardness is ± 0,18%.

WOOD examined also another geometrical error of the Vickers indenter, namely when the cross section permendicular to the pyramid axis is not a square but a rhombus. The error in hardness in the case of a pyramid having a rhombus base with an angle of Θ (in place of 90°) was found to be :

$$\Delta \mathrm{HV} = - \left(\frac{1 - \mathrm{tg}\, \Theta/2}{1 + \mathrm{tg}\, \Theta/2} \right)^2 \qquad (15)$$

This error is practically negligible. Even if $\Theta = 91°$, Δ HV is less than 0,01%. Nevertheless NPL prescribes a tolerance of ± 0,2° on the 90° angles, because in practice it is reasonably easy to define this angle correctly on a lapping machine, and the practical advantage to be gained is that the cause of indentations, where one diagonal is longer than the other, cannot be attributed to the form of the indenter and must therefore be caused by a property of the test piece.

The line of junction between opposite faces (in place of meeting in a point) should not be longer, according to ISO 146, than 2 µm for HV 1 to HV 100, and 1 µm for HV 0,2 to less than HV 1. The effect of the line of junction (ridge) on measured hardness was examined by WOOD et al. (W-22) and by BLAZEWSKI and MIKOSZEWSKI (B-9). The formula of WOOD is :

$$\Delta \mathrm{HV} = - \frac{1}{1 + \left(\frac{d}{r}\right)^2} \qquad (16)$$

where d is the length of the measured diagonal and r is the ridge length. The presence of a ridge will introduce negative errors, or softer apparent hardness. A ridge length of $r = 2$ µm results in a hardness error of only 0,04% if $d = 100$ µm, and 0,58% if $d = 25$ µm. But in the case of an indentation of 10 µm, already a ridge length of 1 µm gives 1% error in hardness.

The corresponding formula given by BLAZEWSKI and MIKOSZEWSKI is :

$$\Delta \mathrm{HV} = - \frac{r^2}{2\, d^2} \qquad (17)$$

which supplies error values which are practically the half of those obtained by the other formula.

BARBATO (B-4) indicated that for Vickers tests with low loads sometimes very strict tolerances are given for the ridge. This may create serious difficulties both in the manufacture of indenters and also in the control of indenter geometry. It should be taken into account that the prescribed values are very close to the separating capability of the optical microscope which can be set as being above 0,3 µm in green light.

8.3. Steel ball

Standard specifications for HB, HRB and HRT indenters indicate that steel balls produced for the ball bearing industry generally satisfy the requirements of hardness testing. YAMASHIRO et al. (Y-10) examined the effect of ball diameter errors on Rockwell superficial (HRT) hardness values. In the case of steel balls with diameters not exceeding tolerance limits, a hardness error of 0,15 HRT was found at the maximum, what is considerably below the uncertainty of standard equipment.

At HRB measurements specified ball diameter tolerances result in hardness changes less than ± 0,2 HRB above the hardness level of 30 HRB (Y-9). The effect of changing the 10 mm ball diameter considerably, by up to 1,5 mm, on measured Brinell hardness values was examined by LIN-ZÜ-ZEI and YANG DI (L-3). The results correspond to theoretical expectations, but need not to be employed in metrological practice where geometrical errors of this magnitude can be avoided.

8.4. Inclination of the indenter

This error source is frequently neglected. Two cases, which are similar, though not identical in their effect, may arise. In Fig. 28, under a, that case is illustrated when the indenter axis coincides with the line of action of the test force, and is perpendicular to the surface of the specimen, but the diamond cone or pyramid axis is inclined with respect to the indenter axis.

In the case designated by b in Fig 28, the cone or pyramid axis coincides with the indenter axis and with the line of action of the test force, but the surface of the specimen is not perpendicular to the direction of penetration.

Standard specifications give tolerance values only for case a. Both cases were examined, theoretically and by experiment by MIKOSZEWSKI and BOLESLAWSKA (M-18, M-19), further by YUAN FENG-ZHONG (Y-16). The influence of an angle of inclination γ of the diamond cone with respect to the indenter axis (case a) is shown in Fig.29. Calculated values are given for different γ values. Inclinations up to 1°30' resulted in errors of hardness below 0,2 HRC. This fact proves that the tolerance of 30' specified in standards is well founded.

A precondition of this moderate influence is that the diamond is embedded in the holder (mounting) absolutely securely. KOHLER and FEUCHT (K-6) found several Rockwell C indenters supplying always lower hardness values than expected according to geometrical data. By measuring indentation depth directly on the edge of the diamond cone a displacement (tilting) of the diamond tip with respect to the steel holder under the test load was established. After the removal of the test load this tilting was recovered, i.e. it was an effect of hysteresis character. The error of measurement introduced went up to 1 HRC. Some indenters were originally correct, the described tilting appeared only after some 1500 measurements.

MIKOSZEWSKI (M-22) examined 20 HRC-indenters and found elastic deformations under total load going up to 15 µm, the mean value being 3 µm at low and 5 µm at high hardness values. The remanent part of the indenter deformation at removal of the additional load was not determined separately. The very high elastic deformation values show that one of the main advantages of diamond as an indenter material, namely its rigidity, may be lost by employing a not reliable embedding technology.

On hardness standard equipment the perpendicularity of the indenter axis to the surface of the specimen is ensured, thus case b in Fig.28 may arise practically only on industrial type hardness testers. For an inclination of β = 3°, hardness errors up to 0,5 HRC are given in (M-18 and H-6). This effect, however, greatly depends on the model of the hardness tester, on tolerances of the guiding of the indenter, i.e. it may be different for each tester, or even for each position of the indenter, as the direction of load is changing during the indentation process.

Thus two Japanese research workers mentioned in (Y-14) found hardness errors of 0 - 0,5 and 0,4 - 0,6 HRC for β = 2°, and of 0,5 - 1,5 and 1,2 - 1,7 HRC for β = 3°. The first value given applies for high, while the second for low hardness levels. All these errors have a negative sign.

In the case of Vickers hardness the effect depends also on the relative position of the diagonal of indentation to the slope of the specimen. Fig.30 shows the magnified indentation when one diagonal is in the direction of inclination (a), or including an angle of 45° therewith (b). An inclination angle of β = 3° results in an error of approximately 0,2% of the Vickers hardness value (W-13) what is not very high.

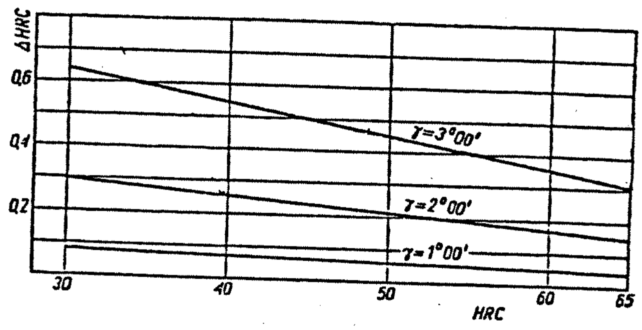


Figure 29

Error in HRC hardness at the effect of an inclination of the indenter according to Fig. 28 a, in function of hardness level.

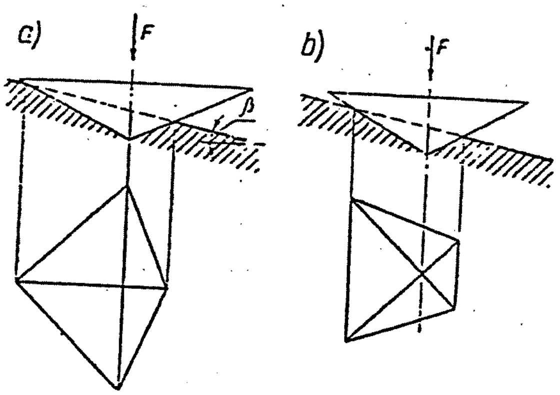


Figure 30

Different relative positions of the HV indentation on an inclined test surface.

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STANDARDS AND RECOMMENDATIONS

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

SR - 2 ISO/R 1024-1969 Rockwell superficial hardness test (N and T scales) for steel.

SR - 4 ISO 6507/1-1982 Metallic materials - Hardness test - Vickers test - Part 1 : HV 5 to HV 100.

SR - 5 ISO/DIS 6507/2 Metallic materials - Hardness test - Vickers test - Part 2 : HV 0,2 to less than HV 5.

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 - 13 ISO/R 146-1968 Verification of Vickers 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 - 26 OIML I.R. n°11. Verification and calibration of Rockwell B hardness standardized blocks.

SR - 27 OIML I.R. n°10. Verification and calibration of Vickers hardness standardized blocks.

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