INFLUENCE OF THE INDENTER SHAPE IN ROCKWELL HARDNESS TEST

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ABSTRACT

One of the main problems related to Rockwell hardness measurements is the influence of the indenter shape. In the present work the effects of the macro-geometry of the diamond indenter are analyzed as influencing parameters in Rockwell C test. Both an experimental analysis is carried out, using IMGC National Standard Machine, and a finite element simulation (FEM) is performed.
Four different theoretical models are proposed to interpret experimental results: the first model is based on Brinell definition of hardness, the second on Meyer analysis and the last two are based on the evaluation of the deformation work through the analysis of the indentation volume. These different corrections are compared to evaluate their performances.

1. INTRODUCTION

Hardness measurements represent one of the most convenient methods for quality assurance in the field of mechanical characterization of materials. Due to its simplicity and its quickness of execution, Rockwell hardness test is the most widely employed. In last years particular attention has been devoted to the influence of the indenter, which can be considered one of the main source of uncertainty in Rockwell hardness measurements[1, 2]. This influence can be related either to the shape of the indenter (geometry, surface roughness) and to its mechanical behavior (deformations under the action of loads, hysteresis)[3].
The effect of indenter shape is widely investigated and many authors present different kind of approach to solve this problem[4, 5]. The errors in Rockwell C hardness values caused by angle and radius errors of the indenter are summarized in Fig. 1.a and Fig. 1.b[1, 6, 7, 8, 9]. The zone between the two continuous lines contains the errors, as resumed by Petik[1], due to a radius difference of +0,01 mm and an angle difference of +30'. Inside of the two included zones the lines corresponding to the theoretical evaluation due to Bochmann & Hild (corresponding to "Brinell method")[6, 10] and the regressions proposed by Yamashiro & Uemura[8] and Stepanow[7] are reported.
Fig. 1.a and Fig. 1.b are in agreement with the practical rule proposed by Yamamoto & Yano[11], according to which the uncertainty of hardness standardizing machines due to shape errors of the indenter should be of the order of ±1 HRC.
It must be noted that other experimental data by Wood et al.[12], who analyzed the performance of 20 indenters from 5 different producers, result into an hardness error higher than the zone given in Fig. 1.a and Fig. 1.b.

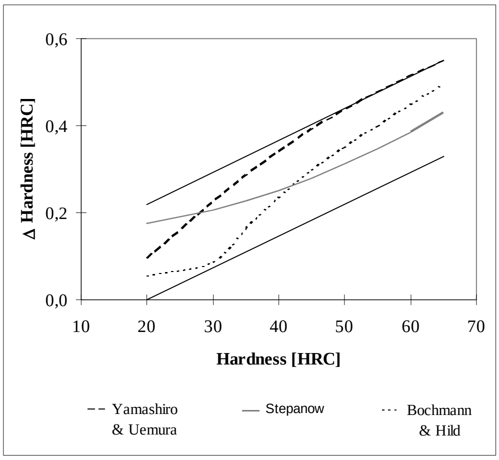

Fig.1.a. Hardness errors due to a radius deviation of +0,01 mm in function of the hardness level.

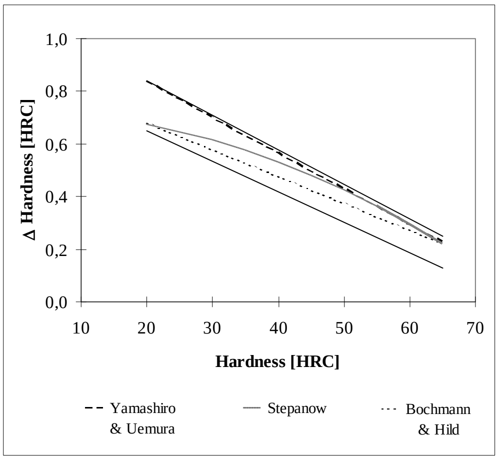

Fig.1.b. Hardness errors due to an angle deviation of +30' in function of the hardness level.

The problem has two main drawbacks: on the one hand the experimental plans of the star type that seems to be used in the past cannot give information about second-order effects, on the second hand factors outside of geometry can produce an experimental noise that hide geometry effects. For these reasons we tried to use an experimental plan based on a factorial and a star scheme compared with the results obtained by the simulation with FEM.

To keep small the relative effect of various influence quantities, like surface roughness and mechanical properties of the indenter, the analysis has been performed on a sample field much larger than the standard tolerances, ranging from about 118° to 122°, for the cone angle, and from 180 μm to 220 μm, for the tip radius.

2. EXPERIMENTAL ANALYSYS

The experimental analysis has been performed using three calibration blocks having respectively the following hardness levels: 25 HRC, 44 HRC and 55 HRC. As previously reported, nine different diamond indenters, arranged following a factorial and a star scheme, have been utilized in order to find out first and second-order effects of the radius and of the cone angle. Indenter dimensions are given in Table 1.

The spherical tips of indenters have been characterized using the IMGC measurement system[13]. Four sections of each tip have been measured. Average values of the four radii related to the above mentioned sections are reported in Table 1. The relevant extended uncertainty (2σ) is of about 0,4 μm.

The measurement of cone angle has been performed using IMGC device based on optical interference, which allows obtaining result affected by an extended uncertainty (2σ) of the order of 0,03°.

For each calibration block, five hardness measurements have been performed using the IMGC dead-weight testing machine[14]. In Table 1 average values for each block are reported.

The extended uncertainty (2σ) related to each of those average values has been estimated to be of the order of 0,15 HRC.

Table 1. Hardness values (H) measured for each hardness level with the nine indenters and differences (ΔH) from central values (estimated with the averages of the results coming from all corrections).

Indenter			Hardness level: 25 HRC		Hardness level: 44 HRC		Hardness level: 55 HRC	
Nr.	Tip radius [μm]	Cone angle [°]	H [HRC]	ΔH [HRC]	H [HRC]	ΔH [HRC]	H [HRC]	ΔH [HRC]
1	175,5	118,62	22,68	-2,36	41,92	-2,28	52,64	-2,10
2	192,3	118,64	22,91	-2,13	42,27	-1,93	52,83	-1,91
3	227,7	118,33	23,54	-1,50	43,57	-0,63	54,69	-0,05
4	180,8	120,38	25,33	0,29	44,08	-0,12	54,37	-0,37
5	205,8	119,96	25,19	0,15	44,22	0,02	54,84	0,10
6	202,4	120,41	25,98	0,94	44,92	0,72	55,49	0,75
7	183,5	122,45	28,15	3,11	46,13	1,93	55,92	1,18
8	185,9	122,37	28,16	3,12	46,32	2,12	56,04	1,30
9	220,2	122,33	28,70	3,66	47,27	3,07	57,46	2,72

3. FEM SIMULATION

The advantage of this approach is that it allows, in principle, to isolate different contributes of hardness measurement errors. For that simulation the finite element code ABAQUS has been adopted. The problem has been modeled introducing the following input parameters:

- perfectly rigid indenter, shaped with required tip radius and cone angle;
- cylindrical specimen with sufficiently large radius;
- specimen constructed with homogeneous material;
- friction coefficient between specimen and indenter η = 0;
- characteristic parameters for the elasto-plastic deformations of the tested material.

Due to the geometry of the problem it is possible to analyze it with an axialsymmetric model, which allows reducing remarkably the complexity of the simulation. Therefore the analysis has been performed on a radial section of the specimen and of the indenter, shown in its main dimensions in Fig. 2 and, for the indentation zone, in Fig. 3 (radial section of the indentation after the removal of the major load).

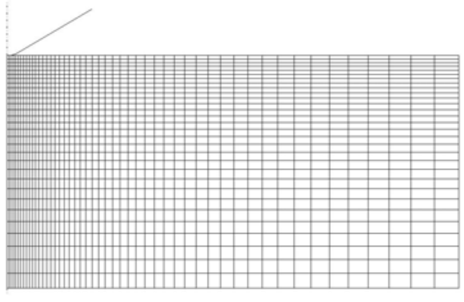

Fig. 2. Scheme of the model utilized for the simulation.

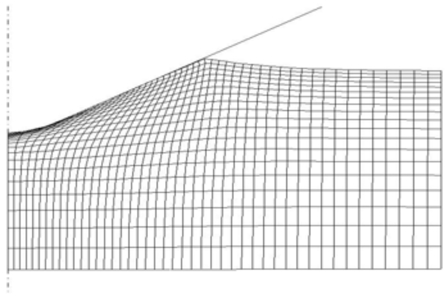

Fig. 3. Shape of the indentation impression after the removal of total load.

In Table 2 the differences between simulation and experimental results are reported. It must be specified that, as found by a careful analysis, the effect introduced with the discretization of the indenting domain produces an extended uncertainty (2σ) of the order of 0,3 HRC.

4. RESULTS ANALYSIS

Some differences from experimental and simulation results exist; they are reported in Table 2. Those discrepancies seem to become bigger with the increasing of the hardness. The reason of that has to be found in the limits of both the experimental analysis and the simulation. Experimental results are mainly affected by three sources of error: the indenter shape, which could not be so regular as in a ideal case, the indenter roughness, which depend on machining differences, and the indenter hysteresis, which is due to the production technology.
On the other side, simulation data present errors coming from the domain discretization and from the assumptions done for the construction of the model. Particular influence is due to contact parameters at the interface between indenter and specimen, for that reason friction coefficient η and surface discretization of sample are supposed to be the main source of error.

Table 2. Differences between simulation and experimental data.

Indenters		Difference between simulation and experimental data [HRC]		
Tip radius [μm]	Cone angle [°]	Hardness level: 25 HRC	Hardness level: 44 HRC	Hardness level: 55 HRC
175,5	118,62	-0,18	-0,60	-0,21
192,3	118,64	-0,16	-0,21	0,53
227,7	118,33	-0,19	0,26	0,47
180,8	120,38	-0,05	-0,42	-0,56
205,8	119,96	0,01	0,05	0,02
202,4	120,41	-0,07	-0,42	-0,62
183,5	122,45	0,18	-0,37	-0,57
185,9	122,37	0,15	-0,57	-0,63
220,2	122,33	0,26	-0,22	-0,43

Those differences, being justified by uncertainty evaluation, shall be acceptable. For that reason we shall consider the numerical model as validated for this first step of the approach, within the said uncertainties. The purpose for the future work is to reduce those discrepancies increasing the number of elements, at least in the region with the maximal deformation, and to investigate on friction effects.
Experimental data have been analyzed in order to obtain a correction of hardness measurements versus tip radius and cone angle errors. Operating a linear correlation analysis it has not been possible to find out significant second-order effects at hardness levels 25 HRC and 44 HRC. Second-order effects become relevant at 55 HRC level.

Table 3. Relations between tip radius, cone angle and hardness errors (experiment).

Hardness level [HRC]	Formula	Standard deviation [HRC]	Correlation coefficient
25	$\Delta H = 1{,}38 \cdot \Delta\alpha + 0{,}023 \cdot \Delta r$	0,13	0,997
43	$\Delta H = 1{,}05 \cdot \Delta\alpha + 0{,}035 \cdot \Delta r$	0,16	0,993

55	$\Delta H = 0{,}96 \cdot \Delta\alpha + 0{,}045 \cdot \Delta r - 0{,}12 \cdot \Delta\alpha^2 + 0{,}0006 \cdot \Delta r^2$	0,19	0,990

The relations obtained for the three different levels of hardness are reported in Table 3, where ΔH denotes hardness error measured on Rockwell C scale points, $\Delta\alpha$ angle error in degrees, and Δr radius error in micrometers. The results obtained with those relations are on the boundaries of the regions reported in Fig. 1.a and Fig. 1.b.
The same analysis has been performed on simulation results. In this case there are relevant second-order effects at all the three hardness levels, the relations obtained are reported in Table 4.

Table 4. Relations between tip radius, cone angle and hardness errors (simulation).

Hardness level [HRC]	Formula	Standard deviation [HRC]	Correlation coefficient
25	$\Delta H = 1{,}51 \cdot \Delta\alpha + 0{,}024 \cdot \Delta r - 0{,}032 \cdot \Delta\alpha^2$	0.09	0,999
43	$\Delta H = 1{,}07 \cdot \Delta\alpha + 0{,}047 \cdot \Delta r - 0{,}058 \cdot \Delta\alpha^2 +$ $+ 0{,}00035 \cdot \Delta r^2 - 0{,}0044 \cdot \Delta\alpha \cdot \Delta r - 0{,}28$	0,03	0,999
55	$\Delta H = 0{,}594 \cdot \Delta\alpha +$ $+ 0{,}052 \cdot \Delta r - 0{,}021 \cdot \Delta\alpha^2 - 0{,}0019 \cdot \Delta\alpha \cdot \Delta r - 0{,}31$	0,03	0,999

The low values of standard deviation indicate that a great part of random effects have been overcome.
We shall notice, however, that the results obtained with relations in Table 4 are only partially inside of the limits of Fig. 1.a and Fig. 1.b. This is probably due to the fact that sample discretization error has its maximal effect with smaller indentation impression, and this happens during load application in hard materials.

5. PROPOSED CORRECTIONS

Due to the fact that corrections coming from liner correlation of experimental data do not give a physical interpretation of the involved phenomena, it is useful to introduce a different approach to interpret hardness deviations induced by indenter geometry errors. For that reason four different models, based on indenting process interpretation, are proposed.
The first correction take rise from Brinell definition of hardness, according to which, the ratio between applied load and indentation surface should be constant for a given material. The second one is based Meyer analysis, and consists on imposing the invariance of the ratio between applied load and the projection of the indented surface. The last two corrections are based on the evaluation of the deformation work through the analysis of the indentation volume, in that way they are directly correlated to mechanical process during the indentation. It must be remarked that a significant source of error for these corrections is the approximation of the indentation shape with the indenter shape, thus neglecting the effects due to the elastic recovery of the tested material.
For those corrections the four formulas in Table 5 have been utilized.

Table 5. Correction formulas for hardness errors inferred by angle and radius errors.

"Brinell" correction	"Meyer" correction	Volume correction (V1)	Volume correction (V2)

$\frac{F}{S} = k_B$	$\frac{F}{A} = k_M$	$\frac{F}{\left(\sqrt[3]{V}\right)^2} = k_{V1}$	$\frac{F}{\left(\frac{V}{h}\right)} = k_{V2}$

Referring to Table 5, F is the imposed load, S is the contact surface, A is the projection of contact surface, V is the volume of the indenting impression, h is the depth of the impression and k_B, k_M, k_{v1}, and k_{v2} are constants depending on the specimen material. The values of the constants are calculated from the measured hardness values, taking into account the measured geometry of the indenter. Thereafter it is possible to calculate the indentation depth under preload and total load expected for an indenter of ideal shape and, after that, to obtain the corrected values of hardness.

Comparisons between those four corrections for the three level of hardness, directly calculated on our experimental data, are reported in Table 6.a and Table 6.b, where ΔH is the difference between the measurements for each indenter and the central values for each hardness level, which is represented by the average of the results coming from all corrections. In general, mainly with the "Brinell" and "Meyer" criteria, one obtains a reduction of the experimental errors to less than 30%.

It must be noted that the angle deviation of the used indenters is larger than the radius deviation in respect to the standard specifications. In those conditions residuals are bigger when corrections are applied on angle in comparison to radius errors.

Table 6.a Comparison between corrections at different hardness levels.

Indenter Nr.	ΔH Difference from central value [HRC]							
	"Brinell" correction				"Meyer" correction			
	Hardness level				Hardness level			
	25	44	55	Average	25	44	55	Average
1	-0,37	-0,23	-0,08	-0,23	-0,09	0,13	0,26	0,10
2	-0,32	-0,49	-0,69	-0,50	0,00	-0,23	-0,47	-0,23
3	-0,13	-0,53	-0,55	-0,41	0,10	-0,45	-0,54	-0,30
4	-0,02	0,23	0,27	0,16	-0,12	0,27	0,38	0,18
5	0,11	-0,18	-0,16	-0,08	0,10	-0,21	-0,19	-0,10
6	0,40	0,29	0,39	0,36	0,30	0,21	0,32	0,28
7	0,15	0,40	0,35	0,30	-0,43	0,10	0,15	-0,06
8	0,25	0,60	0,44	0,43	-0,28	0,32	0,23	0,09
9	0,48	0,42	0,39	0,43	-0,06	-0,04	0,00	-0,03
Average	0,06	0,06	0,04		-0,05	0,01	0,02	

Table 6.b Comparison between corrections at different hardness levels.

Indenter Nr.	ΔH Difference from central value [HRC]							
	$\left(\sqrt[3]{V}\right)^2$ correction				$\frac{V}{h}$ correction			
	Hardness level				Hardness level			
	25	44	55	Average	25	44	55	Average
1	-1,38	-1,18	-0,84	-1,14	-0,42	-0,15	0,37	-0,07
2	-0,80	-0,90	-1,04	-0,91	-0,11	-0,31	-0,46	-0,29
3	0,45	-0,05	-0,47	-0,02	0,57	-0,50	-1,52	-0,49
4	-0,53	-0,32	-0,13	-0,32	-0,39	0,05	0,51	0,06

5	0,28	-0,01	-0,06	0,07	0,19	-0,17	-0,30	-0,09
6	0,55	0,42	0,49	0,49	0,34	0,23	0,31	0,29
7	0,13	0,23	0,31	0,22	-0,68	-0,11	0,36	-0,14
8	0,30	0,51	0,45	0,42	-0,51	0,14	0,45	0,03
9	1,51	1,30	1,09	1,30	0,22	0,09	-0,20	0,04
Average	0,06	0,00	-0,02		-0,09	-0,08	-0,05	

6. CONCLUSION

The analysis performed using a factorial and a star experimental plan shows that second order and interaction effects are significant at least for high hardness level. Nevertheless, we shall observe that, even applying regressions completed with the second order terms, the correction is not complete. Therefore experimental results can be considered as affected by other effects connected with micro-geometry (roughness) or mechanical deformations of the indenter under load. For evaluating these effects, an attempt was made to simulate Rockwell hardness measurement with a numerical model based on Finite elements method. The developed simulation permits to obtain a good agreement between experimental and theoretical data in the range of 0,3 HRC, and, being the aim of the work only the analysis of variations, this was certainly encouraging. In fact we shall remark that the level of significance of the regression coefficients, together with correlation coefficients, are usually higher for the simulation results as compared with the relevant experimental results, and the relevant standard deviations are much smaller. This seems to indicate a smaller noise effect, but we shall note that the freedom of FEM results from disturbing effects, like roughness and hysteresis of indenters, is masked by numerical and discretization effects. Therefore it has not been possible to isolate the errors of indenters not produced by the geometrical effects. Much work shall be devoted to an improvement of the simulation, and this could be realized increasing the number of elements in the zones of maximal deformation and evaluating contributions coming from the friction effect.
A second way attempted for isolating non-geometrical effects was to use a fit based on physical interpretations of the involved phenomena. A check was done using the Brinell definition of hardness, as suggested by Bochmann & Hild[6], the Meyer definition and an evaluation based on the indentation volume (V1), as previously attempted[9] and finally a new model based again on the indentation volume (V2). The results show that performances of all this corrections are independent from the hardness level, but “Brinell” correction and V1 correction show a systematic residual effect of the geometry, while “Meyer” correction and V2 correction (that is a modified “Meyer” correction) seems to clean very well the results from geometrical effects, as the residuals appears to be random.
Future work is needed to evaluate possible effects outside the geometrical ones, therefore specific experiments, to evidence effects of mechanical deformation, and a better FEM model, also with the introduction of the effect of friction, are in preparation.

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