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# THE INFLUENCE OF THE METHOD ON THE BRINELL HARDNESS TEST QUALITY

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**ABSTRACT:** *The data obtained by Brinell hardness test with the tungsten carbide ball "HBW" and non - standardized hardened steel ball "HBS" measured by 8 appraisers were compared by Youden plot, MSA, analysis of uncertainty, t-test and analysis of variance (ANOVA). The difference between the results obtained by carbide and steel ball is affected by appraiser. In regard to ambiguous influence of the ball material, valid technical standard as well as relative low cost of the carbide ball, the authors recommend HBW method (carbide ball) for Brinell test.*
**KEYWORDS:** *HBS, HBW, Youden plot, uncertainty, t-test, ANOVA*

## INTRODUCTION

*The data obtained with the tungsten carbide ball "HBW" (specified by standard [1]) and non - standardized hardened steel ball "HBS", used as the indenters, were compared. The hardened steel balls are frequent accessories of older testers or are used as a result of the appraiser's incompetence. The steel balls are used especially in small business, in practice. The hardness is measured only for internal use (input material, informative controls) in that case. Another case is comparability of the older hardness test results carried out by steel ball (e.g. long term tests). It should be noted that measurements of HBW and HBS on the same sample may differ in value due to differences in the tribological characteristics of the indenter-specimen interface. Empirically determined relation of the HBW-HBS difference depending on the hardness of the tests pieces for unalloyed and low alloyed steels shows the increase with increasing hardness of tested material (significant for the values more than 300 HB) [2].*

*The Brinell hardness test uses a machine to press the ball into the surface of the test specimen. The machine applies a test force proportional to the ball diameter and tested material. The load is usually applied for 10 to 15 seconds, alternatively 15-180 seconds for soft metals. Among used hardness tests, the Brinell ball makes the deepest and widest indentation, so the test averages the hardness over a larger part of material, which will more accurately account for multiple grain structures, and any irregularities in the uniformity of the alloy (typical for cast structure) and soft materials. Wide indentations, on the other hand, can impair the surface of specimen [3].*

*By a perfect measurement, one would obtain the true value of a quantity, which is the value consistent with the definition of a given quantity. True values are, by nature, indeterminable because the perfect measurement cannot be performed. In fact, says the International Organization for Standardization (ISO), it is impossible fully to describe the measured value without an infinite amount of information. In other words, the final corrected result of a measurement is, at best, an estimate of the true value of the quantity that someone intended to measure. The measurement uncertainty is a parameter that characterizes the dispersion of the values that could reasonably be attributed to the measured value [4].*

*In principle, the standard ISO/IEC 17025 does not include new requirements concerning measurement uncertainty, but it deals with this subject in more details than the previous version of this standard. A calibration laboratory, or a testing laboratory performing its own calibrations, shall have and shall apply a procedure to estimate the uncertainty of measurement for all calibrations. Testing laboratories shall have and shall apply procedures for estimating uncertainty of measurement. In certain cases, the nature of the test method may preclude rigorous, metrologically and statistically valid, calculation of the measurement uncertainty. In these cases, the laboratory shall at least attempt to identify all the components of uncertainty and make a reasonable estimation, and shall ensure that the form of reporting of the result does not give a wrong impression of the uncertainty. Reasonable estimation shall be based on knowledge of the performance of the method and on the measurement scope and shall make use of, for example, previous experience and validation data [6].*

*Youden plot (analysis) is directed toward interlaboratory comparisons. Youden's main objective was to determine the precision of a procedure and expect all laboratories to meet this level of precision. For the original Youden plot, two samples must be similar and reasonably close in the magnitude of the property evaluated. The axes in this plot are drawn in the same scale: one unit on the x-axis has the same length as one unit on the y-axis. Each point in the plot corresponds to the results of one laboratory (appraiser) and is defined by a first response variable on the horizontal axis and a second response variable on the vertical axis. A horizontal median line is drawn parallel to the x-axis so that there are as many points above the line as there are below it. A second median line is drawn parallel to the y-axis so that there are as many points on the left as there are on the right of this line.*

*The intersection of the two median lines is called the "Manhattan median". A circle is drawn that should include 95 % of the laboratories (appraisers) if individual constant errors could be eliminated. A 45-degree reference line is drawn through the Manhattan median. The advantage of using Youden plot is its unique ability to separate random and systematic errors. An error that is purely systematic will fall on the 45 degree line. A horizontal line drawn from the "45 degree intercept point" to the error vector shows the proper random and systematic components [5].*

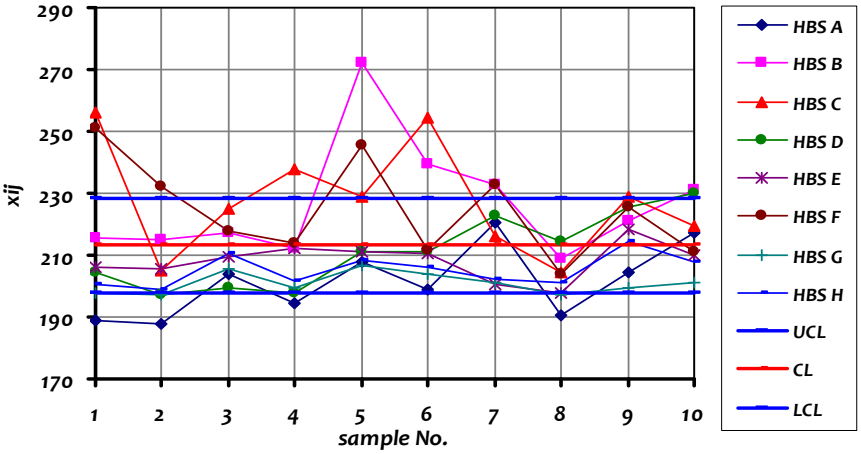


*Figure 1. The hardness HBS*

*Measurement system analysis (MSA) is an experimental and mathematical method of determining how much the variation within the measurement process contributes to the overall process variability. MSA involves GRR (gauge repeatability and reproducibility) studies to evaluate measurement systems. If the analyzed measurement system is capable, it is likely that the measurement process, taking place in it is capable, as well. MSA helps to conform to ISO/TS 16 949:2002 requirements as well as to AIAG standards.*

*The aim of submitted work is to evaluate the quality of the Brinell hardness measurement process, carried out with steel (HBS) and carbide (HBW) balls, using Youden plot, MSA, analysis of uncertainty, t-test and Analysis of Variance (ANOVA).*

## EQUIPMENT, SPECIMEN AND METHOD

*The hardness tester HPO 250 (Veb Werkstoffprüfmaschinen „Fritz Heckert", former East Germany, 1982) with the magnification of measuring device 70x was used as the measurement equipment. The testing force (load) was 1839 N (187.5 kg). The force application time was 15 s. The ratio test force/ball diameter* $\frac{0,102F}{D^2}$ *= 30.01 N mm$^{-2}$ for the ball diameter 2.5 mm. The calibration of both methods (HBS and HBW) realized appraiser D. Two certified reference materials (CRM) in the form of reference blocks were used as the standards, their specified hardness and uncertainty according to calibration certifications is in Table 1.*

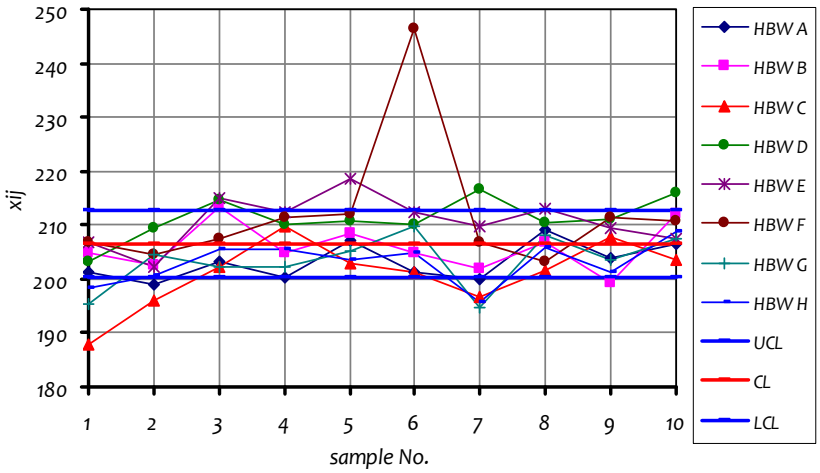


*Figure 2. The hardness HBW*

*The hardness tester is not legal measuring instrument according to Slovak legislative (Metrological Act No. 142/2000 Z. z.), and the metrological confirmation is limited to calibration. The indirect method of calibration according to standard STN EN ISO 6506-2 [7] was used. The repeatability $r_{rel}$, the maximum error $E_{rel}$ (expressed as a percentage of the specified hardness of the CRM) and relative maximum permissible error of the tester (expanded relative uncertainty) $U_{rel}$ may not be more than 2 % for HBS and 2.5 % for HBW (the*

value depends on the standard hardness of CRM). The diameters difference was under 1 % for all indentations. The values of average hardness $\overline{H}$ , standard deviation of the hardness $s_H$, $r_{rel}$, $E_{rel}$ and $U_{rel}$ of calibration are presented in the Table 2. The tester does not satisfy the conditions given in standard regarding $E_{rel}$ and $U_{rel}$ for HBW. It is possible that high value of uncertainty of calibration is the result of low capability (high value of %GRR) [8] and low resolution of the tester.

Table 1. Specified hardness and uncertainty of used standards.

| Standard | specified hardness $H_c$ | U | u |
|---|---|---|---|
| | HBS/HBW | HBS/HBW | HBS/HBW |
| HBS 2.5/187.5 | 242.2 | 3.63 | 1.82 |
| HBW 2.5/187.5 | 185 | 3.30 | 1.65 |

The investigated material were 10 samples of rolled steel STN 41 1600 (equivalent to material E335GC according to standard EN 10025A1). The microstructure is pearlitic with low ferrite content.

The hardness of the samples was measured in the same manner as calibration (HBS and HBW, three trials on each sample) by eight appraisers (A, B, C…H) in random order. The average hardness values are in Figure 1 and Figure 2.

Table 2. The values for calculation of quality of calibration

| Ball/ Standard | H | $r_{rel}$ | $S_H$ | $E_{rel}$ | $u_H$ | $u_{ms}$ | $u_{HTM}$ | $U_{HTM}$ | $U_{rel}$ |
|---|---|---|---|---|---|---|---|---|---|
| | HBS/HBW | % | HBS/HBW | % | HBS/HBW | HBS/HBW | HBS/HBW | HBS/HBW | % |
| HBS/HBS | 243.18 | 0.41 | 0.790 | 0.40 | 0.4065 | 0.151 | 1.87 | 3.74 | 1.95 |
| HBW/ HBW | 191.20 | 1.51 | 2.493 | 3.35 | 1.1824 | 0.107 | 2.09 | 4.18 | 5.61 |

The first step of the hardness measurement system analysis is to estimate whether the discrimination $\delta_{ms}$ (effective resolution) - the value of the smallest scale division (graduation) of measuring equipment is sufficient. A general rule of thumb is that the discrimination ought to be at least one - tenth of the process variation (standard deviation) $s_H$ [9]. The tester satisfies this condition according to results presented in Table 2. The values of discrimination (resolution, smallest scale division) $\delta_{ms}$ of the tester are in Table 3.

$$\delta_{ms} = \frac{H_{max} - H_{min}}{(d_{max} - d_{min}) \times 1000} \quad (1)$$

where H = hardness, d = diameter of indentation (mm)

Table 3. The values of steel hardness for all ten samples

| Method | appraiser | H | $s_H$ | $\delta_{ms}$ | outliers | Normality | | dependence | |
|---|---|---|---|---|---|---|---|---|---|
| | | HB | HB | HB/d | | p | | u | |
| HBS 2.5/187.5 | A | 201.4 | 15.20 | 0.451 | 2 | F | 0.00007 | I | 1.73 |
| | B | 226.5 | 26.14 | 0.595 | 4 | F | 0.00000 | I | 1.27 |
| | C | 227.7 | 23.00 | 0.516 | 0 | F | 0.051144 | I | 1.78 |
| | D | 211.5 | 15.08 | 0.447 | 1 | F | 0.001661 | D | 2.48 |
| | E | 208.2 | 6.32 | 0.417 | 0 | P | 0.609697 | D | 3.02 |
| | F | 223.9 | 15.92 | 0.485 | 0 | F | 0.035253 | D | 3.29 |
| | G | 201.0 | 4.81 | 0.391 | 0 | P | 0.208918 | D | 2.43 |
| | H | 205.2 | 6.96 | 0.433 | 0 | F | 0.062901 | D | 2.42 |
| | Together | 213.0 | 18.91 | | | | | | |
| HBW 2.5/187.5 | A | 203.2 | 4.77 | 0.400 | 0 | P | 0.109241 | I | 1.22 |
| | B | 206.7 | 6.17 | 0.410 | 0 | P | 0.766972 | I | 1.16 |
| | C | 201.0 | 6.55 | 0.390 | 0 | P | 0.196528 | D | 3.09 |
| | D | 211.2 | 4.12 | 0.426 | 0 | P | 0.14503 | D | 3.28 |
| | E | 210.7 | 5.54 | 0.426 | 0 | P | 0.410633 | D | 2.62 |
| | F | 212.0 | 13.95 | 0.396 | 0 | F | 0.00016 | I | 1.85 |
| | G | 203.3 | 5.46 | 0.400 | 0 | P | 0.456192 | D | 3.24 |
| | H | 203.0 | 4.43 | 0.333 | 0 | P | 0.207839 | I | 1.76 |
| | Together | 206.4 | 8.04 | | | | | | |

Grubbs' test (with significance level a = 0.05) detected more outliers when steel ball was used. The statistical outliers would indicate that the process is suffering from special disturbances and is out of statistical control. The results of Abbé independence test are in tab. 3. The condition of the independence (I) of measured results (with significance level a = 0.05) is u < 1,96 [9],[10],[11].

The normality was estimated by Freeware Process Capability Calculator software, using Anderson - Darling test (with a significant level a = 0.05). The value p for files with normal distribution is more than 0.07 (P - "pass", or F - "fail", tab. 3). The standard statistic methods assume normal probability distribution. In fact, there are measurement systems (files) that are not normally distributed. When this happens, and normality is assumed, the measurement system error can be overestimated [9].

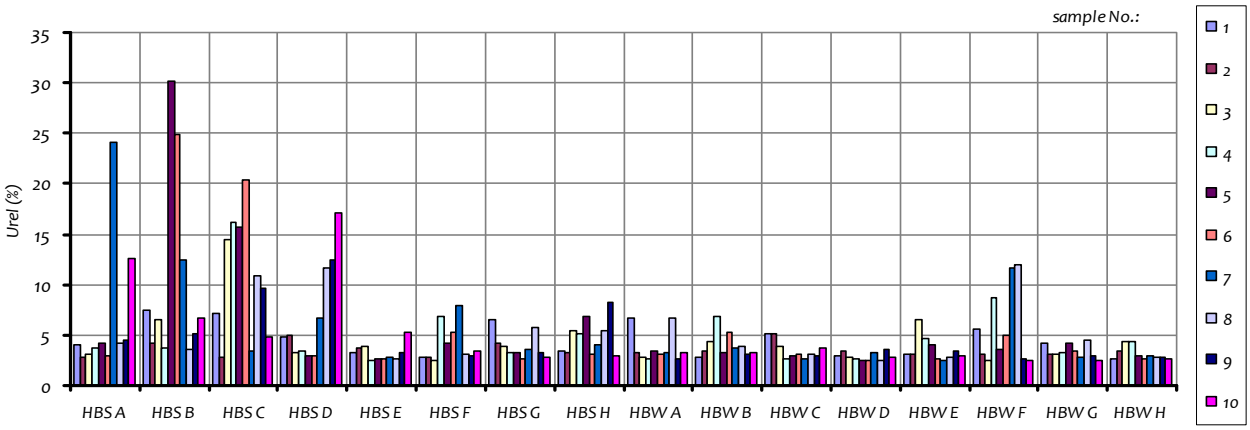


*Figure 3. Values of relative expanded uncertainty for individual samples, appraisers and methods*

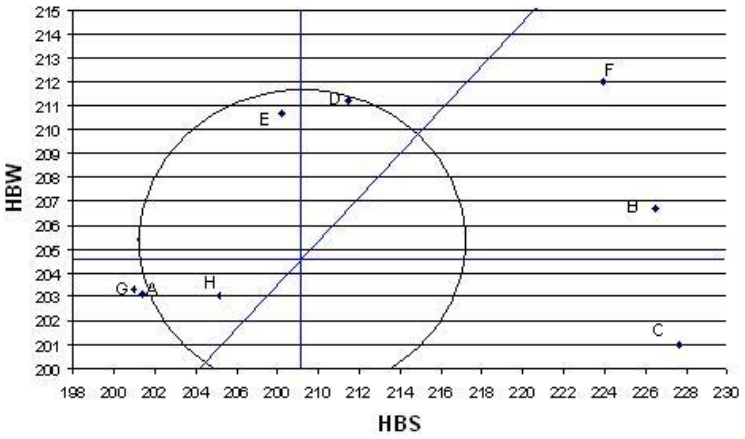


*Figure 4. Youden plot*

*The uncertainties of the hardness of individual sample were calculated according to [1], method "without deviation".*

$$\frac{\Delta U_{HTMmaax}}{H_C} = U_{rel} \qquad (3)$$

*The values of relative expanded uncertainty $U_{rel}$ for individual samples, appraisers and test forces/methods, can be seen in the Figure 3. The average value of $U_{rel}$ for HBS method is 6.35 %, and that of HBW is 3.76 %.*

*The Youden plot (for average hardness of all 10 samples) is in the Figure 4. The best results - minimum total error has appraiser H. The values of total error, systematic error and random error are in the Figure 5. The outliers are appraisers (with total error above the diameter of the circle) A, B, C, F and G. Large correlation was found between total error and average relative expanded uncertainty $U_{relHB}$ ($U_{relHB}^2 = U_{relHSB}^2 + U_{relHBW}^2$) for individual appraisers (r = 0.785).*

## CALCULATION OF HARDNESS MEASUREMENT PROCESS CAPABILITY

*The Average and Range method (GRR), one of Measurement system analysis (MSA) techniques are an experimental and mathematical method of determining measurement repeatability and reproducibility. This technique allows the measurement system's variation to be decomposed into two separate components, repeatability and reproducibility, but not their interaction. The computation of capability indices was carried out according to [9], [12].*

*The number of samples and trials depends upon the significance of the characteristic being measured an upon confidence level required in the estimate of the measurement system variation. As with any statistical technique, the larger the sample size, the less the sampling variation and the resultant risk will be present. As a rule, 10 samples, 3 trials (repeated measurements on each sample) and 2 appraisers are used for tests. If possible, the appraisers who normally use the measurement equipment should be included in the study.*

*The measurement system ought to be under statistical control before capability is assessed, the range (R) control chart is used. The process is under control if all ranges are between control limits. This condition was not satisfied (Table 4) for both balls. If one appraiser is out of control, the method using differs from the others.*

*Table 4. The capability indices*

| Index | %EV | %AV | %PV | %GRR | ndc | R | %X |
|---|---|---|---|---|---|---|---|
| HBS | 59.0 | 66.2 | 46.3 | 88.7 | 0.738 | 1A 2B 4C 1D | 22.5 |
| HBW | 57.2 | 61.8 | 54.0 | 84.2 | 0.904 | 3F 2A 1B 1E | 22.5 |

*The number of distinct categories ("ndc", based on Wheeler's discrimination ratio) is connected with the question of the resolution of measurement equipment. It indicates the number of various categories, which can be distinguished by measurement systems. It is the number of non-overlay 97 % confidence intervals, which cover the range of expected variability of the product. The "ndc" is greater than or equal to 5 for capable processes, results with "ndc" values between 2-5 may be conditionally used for rough estimations (calculations). The "ndc" value is unsatisfactory for both balls.*

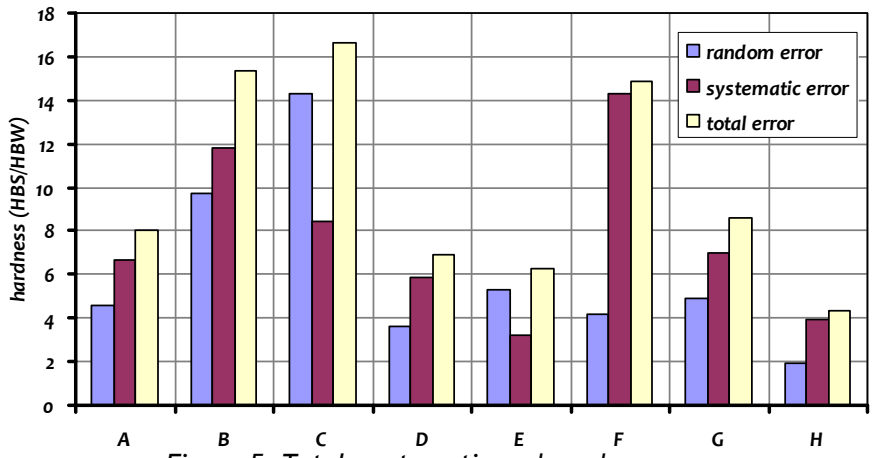


Figure 5. Total, systematic and random error

*The area within the control limits of the X-bar quality control chart represents measurement sensitivity ("noise"). Since measurements used in the study represent the process variation, approximately one half or more of the averages should fall outside the control limits. The measurement system lacks adequate effective resolution or the sample does not represent the expected process variation if it doesn't. As can be seen in Table 4, the condition of sensitivity was not satisfied for both balls.*

*The %EV index represents the cumulative influence of measurement equipment, method and environmental conditions on the variability. It is a function of average range of trials of all appraisers. The difference between %EV indices for HBS and HBW methods is inexpressive.*

*%PV index is a function of range of average hardness of individual samples. It is sensitive to the variability between measured samples. Its value indirectly defines propriety of equipment for measurement. The value of %PV above 99 % stands for ultra accurate and too expensive equipment, above 90 % for suitable and above 70 % for satisfactory one. Used hardness tester is unsuitable for steel ball and inaccurate for carbide ball [13].*

*%AV index represents the influence of appraisers on variability, for example, their competence, perception, skill, discipline and vigilance. It is a function of average values of particular appraisers. Low difference between %AV obtained by HBS and HBW proves that all appraiser keep both methods under control. High numerical value of index proves significant difference between appraisers work.*

*Analyzed process is not capable of both balls as the value of %GRR (the rate of the manufacturing production process variability "consumed" by the measurement system variation) is above 10 %. The difference between capability of HBS and HBW measurement is negligible.*

*Low capability (and high uncertainty) is typical for hardness measurement. The %GRR index varied between 40.9 % and 86.5 % at repeated hardness (HBS 2.5/187.5) measurements of steel (STN 41 1373) [14]. Low capability (between 63.7 % and 89.4 %) had also hardness (HBS 5/250) measurement process of Cu-Zn-Al brass castings [15].*

## THE UNPAIRED T-TEST TO COMPARE TWO MEANS AND FACTOR ANALYSIS

*The average (mean) values of the hardness measured by steel and carbide balls were compared by paired t-tests (95 % confidence interval). The differences for appraisers B and C are statistically significant ($p < 0.05$), Table 5.*

Table 5. T-test, the p-values

| appraiser | A | B | C | D | E | F | G | H |
|---|---|---|---|---|---|---|---|---|
| paired t-test | 0.6291 | 0.07 | 0.0021 | 0.9337 | 0.3458 | 0.1121 | 0.2018 | 0.254 |

*According to Two Factor ANOVA (Analysis of Variance) without replication, the influence of the difference between appraisers ($p = 4.07$ E-8 for HBS and $p = 1.09$ E-5 for HBW) and difference between samples ($p = 0.013599$ for HBS and $p = 0.004015$ for HBW) are both statistically significant.*

*According to Two Factor ANOVA with replication (ten replications are values of ten samples, the first factor are appraisers and the second factor are methods/balls) the influence of the difference between appraisers ($p = 0.00437$) and the difference between methods ($p = 2.6$ E-7) are both statistically significant. The effect of interaction between components is also statistically significant ($p = 0.1.03$ E-5) [16].*

*The influence of the methods/balls and appraisers on the hardness value is more significant than it is in a similar experiment carried out by the group of four appraisers [17] or if the uncertainty is calculated using the tolerance (safe area) analysis [18].*

## CONCLUSIONS

1. *The difference between the results obtained by carbide and steel ball in Brinell hardness test is affected by appraiser.*
2. *The difference is more significant according to ANOVA and analysis of uncertainty.*
3. *The difference of capabilities of hardness measurement by different balls is negligible*
4. *In regard to aforesaid ambiguous influence of the ball material, technical standard in force as well as relative low cost of the carbide ball, the authors recommend HBW method (carbide ball).*

## ACKNOWLEDGEMENT

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