THE INFLUENCE OF THE BALL ON THE BRINELL HARDNESS TEST QUALITY

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VPLYV GUĽÔČKY NA KVALITU BRINELLOVEJ SKÚŠKY TVRDOSTI

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Abstrakt

Meranie tvrdosti patrí k najrozšírenejším skúškam mechanických vlastností. Je to rýchla a jednoduchá metóda na určenie vlastností materiálu z malej vzorky. Meranie tvrdostí je často používaná metodika skúšok mechanických vlastností v automobilovom priemysle, či už u finálnych výrobcov, ale aj u subdodávateľov (napr. plechy). V súvislosti s predpokladaným vývojom automobilového priemyslu v SR sa výskum v tejto oblasti javí ako aktuálna výzva. Ako pri každej skúške mechanických vlastností, aj tu je prirodzená požiadavka na zabezpečenie kvality výsledkov.

Príslušná technická norma STN EN ISO 6506-1:2005 STN vyžaduje pri meraní používať guľôčky z tvrdokovu (spekaného karbidu, hodnota tvrdosti HBW). Bohužiaľ, súčasťou vybavenia tvrdomerov je často guľôčka z tepelne spracovanej ocele (hodnota tvrdosti HBS), ktorá sa v praxi v mnohých prípadoch zo zotrvačnosti, nevedomosti alebo z finančných dôvodov naďalej používa. Napriek tomu, že odborná literatúra pripúšťa, že pri meraní vzoriek s tvrdosťou do 300 HB rozdiel v hodnotách získaných oboma guľôčkami nie je veľký, cieľom predkladanej práce je vyhodnotiť vplyv oboch typov guľôčiek na hodnotu tvrdosti ocele STN 41 1600. Na porovnanie bola použitá analýza systémov merania (MSA), analýza neistôt, Z-skóre, t-test a dvojfaktorová analýza rozptylu ANOVA.

Meranie realizovali štyria operátori. Tvrdosť sa merala podľa STN ISO 6506 ako HBW a HBS 2,5/187,5. Ako merací prostriedok bol použitý tvrdomer HPO 250, vyrobený firmou Web Werkstoffprüfmaschinen „Fritz Heckert“ (bývalá NDR) v roku 1982, zväčšenie meracieho (optického) zariadenia bolo 70×. Tvrdomer bol nepriamo kalibrovaný (pomocou tvrdomernej doštičky – certifikovaného referenčného materiálu) a bola stanovená neistota kalibrácie pre HBS a HBW. Pre HBW tvrdomer nespĺňa podmienky dané normou.

Pomer variability nameraných hodnôt, daný ich smerodajnou odchýlkou a hodnoty najmenšieho dielika tvrdomera potvrdzuje jeho dostatočnú rozlišovaciu schopnosť. Viac odľahlých hodnôt, stanovených Grubbsovým testom a viac súborov nameraných hodnôt s iným

ako normálnym rozdelením, stanovených Anderson – Darlingovým testom sa vyskytovalo v prípade oceľovej guľôčky. Iné ako normálne rozdelenie súboru vedie v prípade analýzy systémov merania k nadhodnoteniu chyby, teda podhodnoteniu spôsobilosti procesu merania.

Napriek vyšším hodnotám neistoty kalibrácie v prípade HBW priemerná relatívna rozšírená neistota pre HBW bola nižšia ako pre HBS.

Analýza systémov merania (MSA) vychádza z predpokladu, že merací proces realizovaný v spôsobilom, teda kvalitnom systéme je tiež spôsobilý. Pri riešení bol použitý prístup GRR (analýza opakovateľosti a reprodukovateľnosti), ktorý okrem číselného vyhodnotenia celkovej spôsobilosti (%GRR) vyhodnocuje aj vplyv dôležitých prvkov systému: meracieho prostriedku %EV, operátora %AV a medzivzorkovej variability (%PV). Výraznejší rozdiel bol zistený iba v prípade indexov %EV. Jeho vyššia hodnota v prípade použitia oceľovej guľôčky (HBS) svedčí o nižšej kvalite. V oboch prípadoch (HBW aj HBS) je celková spôsobilosť nízka (vysoká hodnota indexu %GRR), čo je pri analýze procesov merania tvrdosti bohužiaľ typické. Histogram normovaných hodnôt svedčí o vyššej variabilite v prípade použitia oceľovej guľôčky.

Metóda Z-skóre sa používa v medzilaboratórnych porovnávaniach. Laboratórium reprezentuje jeden operátor, merajúci jedným typom guľôčky. Odľahlé hodnoty, pri ktorých hodnota Z-skóre prekračuje $|3|$ sa vyskytovali iba pri použití oceľovej guľôčky (operátori B a C).

Nepárovým t-testom sa porovnávali priemerné hodnoty tvrdosti namerané jednotlivými operátormi jednou oceľovou a karbidovou guľôčkou. Štatisticky významný rozdiel bol zistený u súborov nameraných operátormi B a C.

Podľa dvojfaktorovej analýzy rozptylu (ANOVA) s opakovaním rozdiel medzi hodnotami tvrdosti, nameranými oboma guľôčkami štatisticky významný.

Vzhľadom na nejednoznačné výsledky analýz, platnú technickú normu, ako aj na relatívne nízku cenu guľôčky z tvrdokovu (karbidu) autori odporúčajú používanie metódy HBW.

Abstract

The Brinell hardness tester with carbide and steel balls was calibrated and thereafter the hardness of ten samples of steel STN 41 1600 were measured by four appraisers. The uncertainty of calibration and of hardness measurement were calculated. The results obtained with carbide and steel balls were confronted using uncertainty analysis, measurement systems analysis (MSA), analysis of variance (ANOVA), unpaired t-test and Z-score. The hardness tester is not considered satisfactory because the values of U_{rel} and E_r of calibration exceed the values permitted by the standard for both balls. The statistically significant difference between the results of hardness obtained by carbide and steel balls depends on appraisers according to t-test. Measurement system analysis confirmed some influence of used ball materials for the results of individual appraisers on the capability of hardness measurement process in accordance with the results of z-score and ANOVA. The difference between average values of U_{rel} of steel and carbide balls is more significant as at aforesaid methods.

Key words: calibration, HBS, HBW, uncertainty, t-test, ANOVA, Z-score

1. Introduction

The aim of submitted work is to evaluate quality of the Brinell hardness test. The data obtained with the tungsten carbide ball “HBW” (specified by standard [1]) and non –

standardized hardened steel ball “HBS”, used as indenter, were compared. The hardened steel balls are frequent accessories of older testers or are used as the indenter at same time as a result of the appraiser’s incompetence. In practice, the steel balls are used especially in small business, where the hardness is measured only for internal use (input material, informative controls) or laboratory measurement of students. 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. Empirical determined relation of HBW – HBS difference shows the increase of this difference depending up the hardness (more than 300 HB) for unalloyed and low alloyed steels [2].

The Metals Handbook defines hardness as “resistance of metal to plastic deformation, usually by indentation”. However, the term may also refer to resistance to scratching, abrasion, or cutting. The higher the metal hardness, the higher resistance to deformation. Measurement of the macro-hardness of materials is a quick and simple method of obtaining mechanical property data for the bulk material from a small sample [3].

The Brinell hardness test uses a machine to press ball into the surface of the test sample. The machine applies a test force proportional to the ball diameter and the hardness of 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 wider amount 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. A wide indentations, on the other hand, can impair the surface of sample [4].

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 to fully describe the measurand (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 measurand [5].

To ensure that calibration certificates are properly interpreted by all calibration laboratories worldwide, it is critical to state uncertainty values in a uniform manner. Over the years, the community has taken many different approaches to evaluating and expressing measurement uncertainty. In 1993, the final work was published as the Guide to the Expression of Uncertainty in Measurement (GUM), which was eventually printed in 1995. This guide is recognized by EA as the master document on uncertainty of measurement [5, 6].

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.

The degree of rigor needed in an estimation of uncertainty of measurement depends on factors such as the requirements of the test method, the requirements of the client and the existence of narrow limits on which decisions on conformance to a specification are based.

When estimating the uncertainty of measurement, all uncertainty components, which are of importance in a given situation, shall be taken into account using appropriate methods of analysis [7].

Measurement system analysis (MSA) is an experimental and mathematical method of determining how much the variation within the measurement process contributes to 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, realized with steel (HBS) and carbide (HBW) balls, using MSA, analysis of uncertainty, Z-score, t-test and two – factor ANOVA.

2. Experimental work

The hardness tester HPO 250 (Web Werkstoffprüfmaschinen „Fritz Heckert“, former East Germany, 1982) with the magnification of measuring device 70× was used as the measurement equipment. The testing force (load) was 1839 N (187.5 kg). The ratio test force/ball diameter $\frac{0{,}102F}{D^2}$ = 30.01 N mm^{-2} for the ball ϕ 2.5 mm. The appraiser D realized the calibration by both methods (HBS and HBW). Two certified reference materials (CRM) in form of reference block were used as the standards, their specified hardness and uncertainty according to calibration certifications are in tab. 1. The force had been applied for 15 seconds.

The hardness tester is not legal measuring instrument according to Slovak legislative (Metrological Act 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 [8] was used. The repeatability r_{rel}, the maximum error E_{rel} (expressed as percentage of the specified hardness of the CRM) and relative maximum permissible error of the tester (relative expanded 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 less than 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 tab. 2. The tester do not satisfies the conditions given in standard as regards 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) [9] of the tester.

Table 1 Specified hardness H_c and uncertainty of used standards

Standard	H_c (HB)	U (HB)	u (HB)
HBS 2.5/187.5	242.2	3.63	1.82
HBW 2.5/187.5	185	3.30	1.65

Table 2 The values for calculation of quality of calibration

Ball/ Standard	$\overline{H}$	r_{rel}	S_H	E_{rel}	u_H	u_{ms}	u_{HTM}	U_{HTM}	$\Delta H_{HTM\ max}$	$\Delta H_{HTM\ max}/H_c$ (U_{rel})
HBS/HBS	243.18	0.41	0.790	0.40	0.4065	0.151	1.87	3.74	4.72	1.95
HBW/ HBW	191.20	1.51	2.493	3.35	1.1824	0.107	2.09	4.18	10.37	5.61

The investigated material were 10 samples of was rolled steel STN 41 1600 (equivalent to material E335GC according to standard EN 10025A1). The microstructure is pearlitic with low ferrite content (fig. 1, etched with 2% nital).

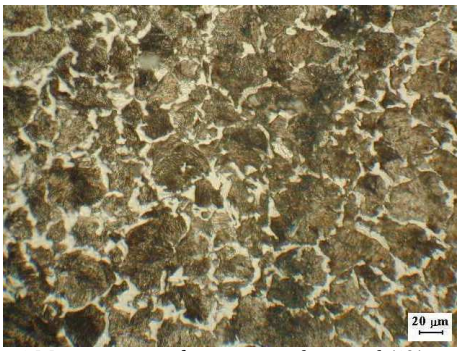

Fig.1 Microstructure of experimental material (1% nital)

The hardness of the samples was measured in the same manner as a calibration (HBS and HBW, three trials on each sample) by four appraisers (A B C and D) in the random chosen order. The average hardness values are on fig. 2.

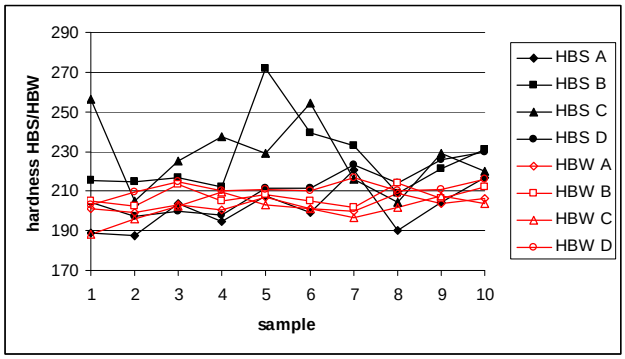

Fig.2 The hardness values

The first step of the hardness measurement system analysis is to estimate whether the discrimination δ_{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 [10]. Looking at table 2, the tester satisfies this condition.

The values of discrimination (resolution, smallest scale division) δ_{ms} of the tester are in tab. 3.

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

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

Grubbs' test (with significance level α = 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 α = 0.05) is u < 1,96 [10, 11,12].

The normality was estimated by Freeware Process Capability Calculator software, using Anderson – Darling test (with significant level α = 0.05). The value p for the 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 [11].

Table 3 The values of steel hardness for all ten samples

method	appraiser	$\overline{H}$	s_H	δ_{ms}	outliers	normality		dependence	
							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
	together	216.8	22.96	-	0	F	0.000000	-	-
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
	together	205.5	6.67	-	0		0.144903	-	-

The uncertainties of the hardness of individual sample were calculated according to [1], method "without deviation". The values of relative expanded uncertainty U_{rel} for individual samples, appraisers and test forces/methods can be seen on the fig. 3.

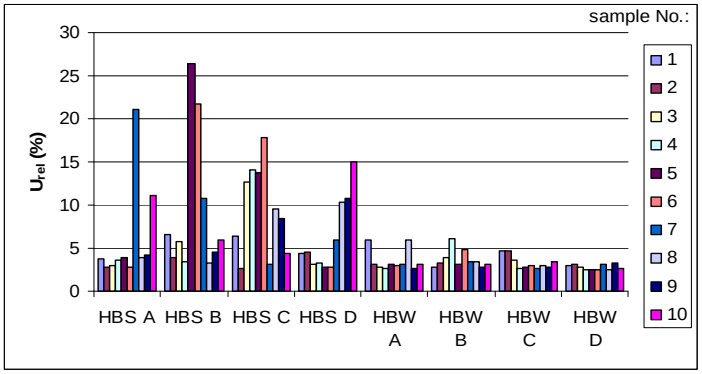

Fig.3 Values of relative expanded uncertainty for individual samples, appraisers and methods

3. Calculation of hardness measurement process capability

The Average and Range method (GRR), one of Measurement system analysis (MSA) techniques is 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 [10, 13].

Table 4 The capability indices

Index	%EV	%AV	%PV	%GRR	ndc	%R	%X
HBS	67.4	57.9	45.8	88.9	0.727	1A, 2B, 1C	15
HBW	51.9	69.9	49.1	87.1	0.0.795	2A, 1B	25

The software Palstat CAQ with significance level α = 0.01 and confidence level α = 0.01 (5.15 σ) was used for capability calculation.

The number of samples and trials depends upon the significance of the characteristic being measured an upon confidence level required in the estimate of 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 (tab. 4) for both balls. If one appraiser is out of control, the method used differs from the others.

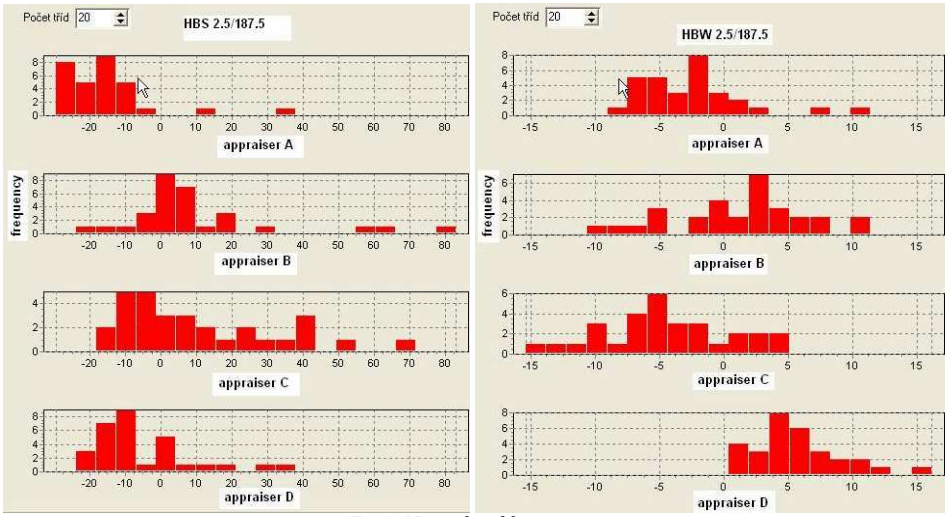

Fig.4 Normalized histogram

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 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.

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. If data show this pattern, then the measurement system should be adequate to detect (sample - to - sample) variation and the measurement system can provide useful information for analyzing and controlling the process. If less than half of the averages fall outside the control limits then either the measurement system lacks adequate effective resolution or the sample does not represent the expected process variation. 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 values of %EV are increased for HBS.

%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 suitability of the equipment for measurement. The value of %PV above 99 % stands for very accurate equipment, above 90 % for suitable, above 70 % for satisfactory and above 50% for inaccurate one. The equipment with value up to 50 % is unsuitable [14]. Used hardness tester is unsuitable for both balls.

%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 from individual appraisers. Less variability of %AV as well as that of %EV make similar quality of all appraisers work.

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

Normalized histogram – histogram plot (fig. 4) is a graph that displays the frequency distribution of the gage error of appraisers who participated in the study. The graph provides a quick overview how the error, i.e. difference between observed value and reference value (samples average) is distributed. The least error (bias) and variability has appraiser B at HBW, the variability of HBS is more pronounced than that of HBW.

The difference between average values of relative expanded uncertainty (U_{rel}) of hardness measurement (7.71 % for HBS and 3.35 % for HBW) is more significant as that of %GRR indices.

Low capability (and high uncertainty) is typical for hardness measurement. The capability of measurement of the hardness of Al-Si castings depends on microstructure, modified by cooling rate. The values of %GRR were between 42.2 % (fine microstructure) and 71 % (coarse, needle shaped particles of eutectic Si). The %GRR index varied between 40.9 % and 86.5 % at repeated hardness (HBS 2.5/187.5) measurements (8 times) of steel (STN 41 1373) [15]. Low capability (between 63.7 % and 89.4 %) had also hardness (HBS 5/250) measurement process of Cu-Zn-Al brass castings [16].

4. The calculation of Z-score

The Z-score method, routinely applied in interlaboratory comparison tests was used for validation of above mentioned results. The value for individual sample is:

$$z_i = \frac{x_i - \bar{x}}{s_H} \tag{2}$$

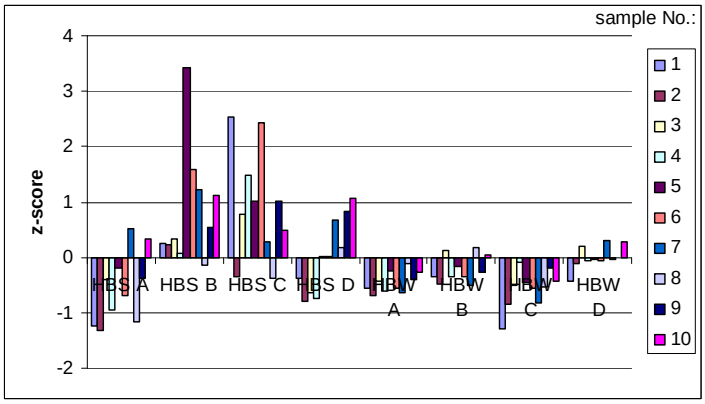

Fig.5 Z-score

x_i is the average hardness of all trials of i-sample (i = 1 - 10), $\bar{x}$ the average hardness of i-sample measured by all appraisers with both balls and s_H is standard deviation of i-sample hardness measured by all appraisers with both balls. The results $|z_i| \leq 2$ are satisfactory and $|z_i| \geq 3$ are unsatisfactory [17]. As can be seen on the fig. 5, the difference between z-score results obtained by HBS and HBW is significant, especially for appraisers B and C.

5. The unpaired t-test to compare two means and the factor analysis

The average (mean) values of the hardness measured by steel and carbide balls on all samples were compared by unpaired t-test with 95 % confidence interval. The differences between balls for appraisers B (p = 0.0002) and C (p = 0.0001) are statistically significant in contrast to differences for appraisers A (p = 0.5536) and D (p = 0.9277).

According to Two Factor ANOVA (analysis of variance) without replication, the difference between appraisers (p = 0.000457) is statistically significant and the difference between samples (p = 0.092826) is not statistically significant for the hardness measured by steel ball. The difference between appraisers (p = 0.00000622) and difference between samples (p = 0.010226) are both statistically significant for carbide ball. The carbide ball (HBW method) is more sensitive to differences of sample hardness.

According to Two Factor ANOVA with replication (four replications are values of four appraisers, the component No. 1 are methods/balls and component No. 2 are samples) the difference between methods (p = 0.000538) is statistically significant and the difference between samples (p = 0.299791) is not statistically significant. The effect of interaction between components is not statistically significant (p = 0.426205) [18].

The ambiguous influence of the ball and interaction between hardness and appraisers was observed in similar experiment carried out by group of four another appraisers [19].

6. Conclusion

1. The uncertainty of the hardness measured by steel ball exceeds the uncertainty of the hardness measured by carbide ball.

2. The difference between the values of hardness measured by different balls is statistically significant for appraisers B and C.
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).

Acknowledgements

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