AVALIAÇÃO DA INCERTEZA DE MEDIÇÃO NO ENSAIO DE DUREZA BRINELL: GUM E MÉTODO DE MONTE CARLO

MEASUREMENT UNCERTAINTY EVALUATION OF BRINELL HARDNESS TEST: GUM AND MONTE CARLO METHOD

TREVISAN, Lisiane[1*]; FABRICIO, Daniel Antonio Kapper[2]

[1]Instituto Federal de Educação, Ciência e Tecnologia do Rio Grande do Sul – IFRS, Campus Farroupilha
Av. São Vicente 785, CEP 95180-000, Farroupilha – RS, Brasil
(fone: +55 54 3260.2400)

[2]Instituto Federal de Educação, Ciência e Tecnologiade Santa Catarina – IFSC, Campus Chapecó
Av. Nereu Ramos, 3450-D, CEP 89813-000, Chapecó – SC, Brasil
(fone: +55 49 3313.1245)

** Autor correspondente*
e-mail: Lisiane.trevisan@farroupilha.ifrs.edu.br

Received 12 June 2000; received in revised form 14 March 2018; accepted 16 March 2018

RESUMO

O ensaio de dureza Brinell é um dos ensaios mecânicos mais utilizados pela indústria para garantir a qualidade de processos metalúrgicos. Com base nos valores medidos, é necessária a descrição dos valores de incerteza de medição associados ao método matemático utilizado. Assim, o valor da incerteza de medição descreve a confiabilidade nos resultados obtidos experimentalmente. A metodologia do cálculo da incerteza de medição pode ser realizada de várias formas, sendo o método descrito pelo ISO GUM o mais utilizado pelos laboratórios acreditados pela norma ISO/IEC 17025. Este artigo tem como objetivo principal comparar valores de incerteza de medição obtidos com base em diferentes fontes de incerteza utilizadas na avaliação da incerteza de medição para dois laboratórios brasileiros acreditados pela Cgcre/INMETRO. Além disso, também serão mostrados os valores de incerteza obtidos pelo método GUM e pelo método de Monte Carlo. Os resultados mostram que não há grande variação nos valores de incerteza de medição em função do método matemático utilizado.

Keywords: *Incerteza de Medição, Brinell, Monte Carlo.*

ABSTRACT

The Brinell hardness test is one of the most used mechanical tests in the industry to assure the quality of metallurgical processes. Based on the measured values, it is necessary to describe the measurement uncertainty values associated with the mathematical method used. Thus, measurement uncertainty values describe the reliability of the experimental results. The calculation of measurement uncertainty can be performed in several ways, and the method described by ISO/GUM is the most used by ISO/IEC 17025 accredited laboratories. The main objective of this work is to compare measurement uncertainty values based on different sources of uncertainty used in the measurement uncertainty evaluation for two Brazilian laboratories accredited by Cgcre/INMETRO. In addition, uncertainty values obtained by the GUM method and by the Monte Carlo method were compared. The results show that there is no great variation in the measurement uncertainty values as a function of the mathematical method used.

Keywords: *Measurement uncertainty, Brinell, GUM, Monte Carlo.*

DOI: 10.52571/PTQ.v15.n30.2018.255_Periodico30_pgs_252_258.pdf

INTRODUCTION

The Brinell hardness is one of the most used mechanical tests because it is a simple test in which a load is applied through a steel sphere where an indentation is demarcated on the surface of the sample [1]. The hardness value in the Brinell scale (HB) is related to three parameters through a mathematical equation: test force applied, indenter diameter and indentation diameter [2].

Several factors justify the evaluation of measurement uncertainty in the field of testing and calibration. Through the uncertainty value, it is possible to verify the reliability of the results, allowing the approval within the tolerance limits specified by the customer. At this stage, the accreditation of the laboratory with the certification bodies is fundamental to assure reliable average values and measurement uncertainty.

The Guide to the Expression of Uncertainty in Measurement (GUM) [3] was elaborated in order to harmonize the methodologies used by metrological laboratories for the evaluation of uncertainty in measurement, as well as to serve as a guide for easy understanding and implementation in the different areas of metrology [4].

The GUM presents a methodology for the evaluation of measurement uncertainty based on the Law of Propagation of Uncertainty (LPU), and the characterization of the output quantity through a normal (Gaussian) distribution or a weighted Student's distribution [5].

The GUM uncertainty framework begins on the mathematical definition between the measurand Y and the input quantities Xi, that is, $Y = f(X_1, X_2, ..., X_N)$, where f represents the measurement model. The standard uncertainty associated with each input quantity is evaluated and included in the measurand through the Law of Propagation of Uncertainty, Equation 1 [5-6].

$$u_c^2(y) = \sum_{i=1}^{N}\left(\frac{\partial f}{\partial x_i}\right)^2 u^2(x_i) + 2\sum_{i=1}^{N-1}\sum_{j=i+1}^{N}\frac{\partial f}{\partial x_i}\frac{\partial f}{\partial x_j}u(x_{i,}x_j) \quad \text{(Eq.1)}$$

In Equation 1, uc(y) stands for the combined standard uncertainty; ∂f/∂xi represents the sensitivity coefficients for each variable, calculated as partial derivatives from the measurement model in relation to each variable; u(xi) the standard uncertainties for each variable; and the second term of the equation represents the uncertainty related to the correlation between variables, when it exists.

Finally, expanded uncertainty is calculated by the multiplication of the combined uncertainty to a coverage factor, i.e., U = K.uc(y), where the coverage factor K is obtained from the degrees of freedom of each input quantity for the desired coverage interval [5-6].

The Monte Carlo method, however, is recommended when the input variables for the uncertainty calculation have arbitrarily high values for measurement models with a high degree of non-linearity and distributions of the input data with complex asymmetries as well as non-Gaussian distributions associated with one of the uncertainty sources [7]. In such cases, the uncertainty estimation by the Monte Carlo method tends to be more representative than the ISO/GUM [8].

Results obtained by the Monte Carlo method depend on the generation of random numbers within the probability distribution determined initially for each input quantity and its implementation in the mathematical function. Based on the mathematical function, the number of iterations is an important factor in obtaining the results, so that the larger the number of iterations, the better the results analysis [9]. It is possible to estimate the number of iterations to produce reliable results based on the desired confidence level, and a number between 105 and 106 is recommended in most cases [10].

It is important to study the probability density functions (PDF) associated to the input quantities when performing Monte Carlo simulations since the behavior of input PDF significantly affects the result, and this definition is one of the first steps in applying the method. The definition of input PDFs must always respect the principle of maximum entropy, in which the wider distribution is always considered depending on the level of information about the input quantity. Some probability distributions commonly used in Monte Carlo simulations are [11]:

• Normal: The user defines the mean (the expected value) and the standard deviation associated to the mean. The values closer to the mean are more likely to occur. This distribution is symmetrical and represents a series of natural events. Usually applied for uncertainties coming from certificates.

• Uniform: The user sets the maximum and minimum, and all values have the same probability of occurrence in this distribution. This is the most conservative distribution of all.

• Triangular: The user sets the minimum, maximum, and likeliest values. Values near the likeliest value are more probable to occur.

• t-distribution: the user defines the expected value, the standard deviation associated to this value and the number of degrees of freedom used to obtain the values. This distribution is recommended when there is a finite series of indications for the same value.

Albano [12] has performed a study to verify the influence of probability distribution on the results of proficiency tests. Among other factors to study the PDF, an analysis of the kurtosis was performed, which represents a measure of dispersion that characterizes the flatness of the probability density function. Such parameter indicates whether the distribution is platykurtic (flatter than the normal distribution), mesokurtic (as flattened as the normal distribution) or leptokurtic (pointed and more concentrated than the normal). It was concluded that the results of proficiency tests are affected by thekurtosis of the distribution (which depends on the probability distribution), emphasizing the importance of the analysis of the characteristics of the probability distribution chosen even in other fields.

Different methodologies can be used to estimate the measurement uncertainty in testing. Considering that the GUM, based on the propagation of uncertainties, and the Monte Carlo Method, based on the propagation of distributions, are some of the most widespread and used methodologies worldwide, this work will perform a comparative analysis of the calculation of measurement uncertainty through these two methods.

In this work, results of the measurement uncertainty of Brinell hardness test will be obtained from two Brazilian laboratories accredited by Cgcre/Inmetro. It is important to note that each laboratory presents different sources for the measurement uncertainty evaluation. In addition, the measurement uncertainty values will be calculated using the Monte Carlo method and the GUM considering the same sources of uncertainty indicated by each of the laboratories.

MATERIALS AND METHOD

The metallic material used in this work is a stainless steel SAE 316L, due to their qualities, such as dimensional stability and excellent resistance to corrosion. The SAE 316 L steel has a low carbon content (maximum of 0.03%) when compared to SAE 316 (maximum of 0.08%) [13]. From the same run, 10 specimens were randomly drawn from different bars to minimize the influence of the chemical composition on the hardness values. For each test specimen, 5 measurements were made on the surface planned by the grinding.

The Brinell hardness test has the objective of minimizing the measurement error since the diameter of the penetrator and the printing mark on the surface are used in the calculation. A semiautomatic durometer was used for a sphere of 2.5 mm diameter and aload of 187.5 kgf for 15 seconds. The calibration of the durometer was performed with a standard of 207 HB with anexpanded uncertainty of 4.5 HB at a 95% confidence level. The measured hardness values are shown in Table 1.

The experimentally measured values will be used for the evaluation of measurement uncertainty in two different Brazilian laboratories accredited by ISO/IEC 17025:2005 [14]. Laboratory A (Lab A) has been accredited by Cgcre/INMETRO since 2010 for mechanical testing (including Brinell hardness), while Laboratory B (Lab B) has been accredited since 2008 for mechanical testing. Monte Carlo method simulations were performed using Crystal Ball® software, an Excel supplement [15]. The uncertainty sources used in the measurement uncertainty assessment by the GUM method are described in Tables 2 and 3, with the respective probability distributions determined by the chosen laboratory. These same sources were considered for the measurement uncertainty assessment by the Monte Carlo Method (MCM).

As shown in Tables 2 and 3, the two laboratories chosen for the development of this study consider different sources of uncertainty to evaluate the value of the final measurement uncertainty in relation to the measurand.

Since there is no restriction on the number of uncertainty sources to be considered, the quality management system of each accredited body can determine which sources will be considered or ignored. It is important to note that the number of uncertainty sources considered does not influence the accreditation and certification process by the national accreditation body.

Otherwise, uncertainty sources neglected by an accredited body can be considered on the other, which can lead to differences in the uncertainty values evaluated. In addition, each test laboratory has its own procedures, equipment and environmental conditions, so that the uncertainty sources considered may be different, just as the uncertainty values themselves may be higher or lower.

RESULTS AND DISCUSSIONS

The measurement uncertainty values evaluated for each of the laboratories considering the two calculation methods are presented in Table 4. In the case of Monte Carlo simulations, they were performed with 100,000 iterations at a 95% coverage level. In order to determine the uncertainty by the GUM method for both laboratories, the sources were quadratically summed and the square root was extracted, thus determining the combined uncertainty.

The hardness values performed in the test specimens, despite starting from the same run of the steel mill, did not undergo any heat treatment of homogenization in order to reduce the dispersion of the hardness results. It is important to indicate that the variability of the mean value obtained can be considered acceptable depending on the customer/application for which it is intended.

The mean values of the measurand have presented variations between test specimens: between the highest mean value of the measurand and the lowest, the variation is of 12.2 HB for both the mean values calculated using the GUM method and the Monte Carlo method. This value is considerable when calculated as a percentage of the mean value, around 9%.

When analyzing the measurement uncertainty value independently of the mathematical method used, test specimen number 2 has presented a larger measurement uncertainty when compared to the uncertainty value of the other test specimens. This probably occurred due to the considerable value of standard deviation, because the standard deviation is a considerable uncertainty source in both mathematical methods used in this work.

When analyzing Lab A, the Monte Carlo method presents a small difference in the measurement uncertainty value when compared to the ISO/GUM method. For Lab B, the same behavior occurs in the measurement uncertainty values. Mathematically, the ISO / GUM method considers the uncertainty sources in a more conservative manner, thus projecting larger expanded uncertainty values than the Monte Carlo Method.

By comparing the results for each test specimen individually, there is no significant difference between the values found by the two laboratories or even between the methods, since the uncertainties are large enough to affirm this.

It should be noted that the calculated measurement uncertainty values are representative of this study, for the conditions tested and values used.

CONCLUSIONS

This work was developed with the initial purpose of demonstrating and comparing the measurement uncertainty values for two different Brazilian laboratories accredited by Cgcre/INMETRO in the Brinell hardness test. The objective was reached and the results showed significant differences between laboratories and methods used in the calculation of uncertainty.

It is important to emphasize that the specimens were based on sampling from the same run of the steel mill, submitted to practically the same parameters of cooling and chemical composition, which minimizes the microstructural effects of the stainless steel tested.

It is important to highlight that although the two laboratories studied participate in RBLE (Brazilian Network of Testing Laboratories), these consider different uncertainty sources, which may cause differences in the value of the measurement uncertainty.

In addition, other important results obtained in this work are the measurement uncertainty values obtained by the two most used mathematical methods in the evaluation of measurement uncertainty, showing that there are small differences when using the same sources but changing the method used to evaluate the measurement uncertainty.

REFERENCES

1. Czichos H, Saito T, Smith L 2011 Handbook of metrology and testing. Springer
2. ASTM E1823 2013 Standard Terminology Relating to Fatigue and Fracture Testing. Pennsylvania
3. ISO/GUM 2003 Guide to the Expression of Uncertainty in Measurement. Rio de Janeiro: ABNT, 3rd ed, 120 p
4. Domeneghetti G 2011 A expressão da incerteza de medição em ensaios mecânicos: ISO GUM e Monte Carlo aplicados no ensaio de tração. Dissertation, Instituto Superior Tupy, Joinville
5. JCGM 2008 Evaluation of measurement data: Guide to the expression of uncertainty in measurement
6. Hack P D S, Caten C S T 2012 Measurement uncertainty: literature review and research trends. IEEE Transactions on Instrumentation and Measurement, v. 61, n. 8, p. 2116-2124
7. JCGM 2008 Evaluation of measurement data - Supplement 1 to the "Guide to the expression of uncertainty in measurement" - Propagation of distributions using a Monte Carlo method
8. Trevisan L, Fabricio D A K, Reguly A 2016 Comparison of uncertainty in fatigue tests obtained by the Monte Carlo method in two softwares. Journal of Physics: Conference Series, v. 733, 012029
9. Cox M G, Dainton M P, Harris, P M 2001 Uncertainty and Statistical Modelling. Software Support for Metrology. Best Practice Guide N°6. National Physical Laboratory, United Kingdom
10. Shahanaghi K, Nakhjiri P 2010 A new optimized uncertainty evaluation applied to the Monte-Carlo simulation in platinum resistance thermometer calibration. Measurement. Vol. 43. p. 901-911
11. Gonçalves D R R, Peixoto R A F 2015 Beneficiamento de escórias naaciaria: Um estudo da viabilidade econômica da utilização dos produtosnasiderurgia e na construção civil. Revista ABM - Metalurgia, Materiais e Mineração, v. 71, nov/dez 2015, p. 506-510
12. Albano F 2016 Desenvolvimento de melhorias no processo de provisão de ensaios de proficiência por comparação interlaboratorial. Thesis. Universidade Federal do Rio Grande do Sul, Porto Alegre
13. Callister W 2007 Materials Science and Engineering. 7th ed, New York
14. ISO/IEC 17025 2005 General requirements for the competence of testing and calibration laboratories, Geneva
15. Couto P R G 2008 A estimativa da incerteza de medição pelos métodos do ISO GUM 95 e de simulação de Monte Carlo. Instituto Nacional de Metrologia, Qualidade e Tecnologia.

Table 1. *Brinell hardness values obtained experimentally.*

Test Specimens	Measured values (HB)				
1	143	143	143	148	148
2	138	164	138	143	138
3	143	148	131	143	131
4	131	143	143	148	148
5	143	143	143	143	150
6	143	135	131	135	135
7	143	143	143	135	135
8	150	148	143	150	148
9	131	135	148	143	148
10	143	143	148	150	143

Table 2. *Uncertainty sources considered by Lab A.*

Uncertainty Source	Measurement Unit	Probability Distribution
Experimental standard deviation	HB	Normal
Uncertainty value from calibration certificate	HB	Normal
Resolution of the rule which measures the diameter of the indentation	mm	Rectangular

Table 3. *Uncertainty sources considered by Lab B.*

Uncertainty Source	Measurement Unit	Probability Distribution
Reference standard	HB	Normal
Standard deviation of experimental standard	HB	Normal
The standard deviation of thetest specimen	HB	Normal
Indicating error of calibration certificate	HB	Rectangular
Error associated to temperature variation	HB	Rectangular
Operator reading error	HB	Triangular
Surface imperfections	HB	Rectangular

Table 4. *Measurement uncertainty values obtained from GUM and MCM, presented in HB.*

Test Specimen	GUM		MCM	
	Lab A	Lab B	Lab A	Lab B
1	145.0 ± 5.1	145.2 ± 5.7	145.0 ± 5.1	145.2 ± 5.7
2	144.2 ± 14.2	144.4 ± 14.3	144.2 ± 14.2	144.4 ± 14.3
3	139.2 ± 9.5	139.4 ± 9.9	139.2 ± 9.5	139.4 ± 9.9
4	142.6 ± 8.7	142.8 ± 9.1	142.6 ± 8.7	142.8 ± 9.1
5	144.4 ± 5.3	144.6 ± 6.0	144.4 ± 5.3	144.6 ± 6.0
6	135.8 ± 6.2	136.0 ± 6.8	135.8 ± 6.2	136.0 ± 6.8
7	139.8 ± 6.2	140.0 ± 6.8	139.8 ± 6.2	140.0 ± 6.8
8	147.8 ± 5.2	148.0 ± 5.8	147.8 ± 5.2	148.0 ± 5.8
9	141.0 ± 9.5	141.2 ± 9.8	141.0 ± 9.5	141.2 ± 9.8
10	145.4 ± 5.5	145.6 ± 6.1	145.4 ± 5.5	145.6 ± 6.1