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Incerteza de medição do ensaio de K_{IC} pelo método de Monte Carlo

Measurement uncertainty of K_{IC} testing by the Monte Carlo method

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Resumo: A estimativa da incerteza de medição pelos laboratórios de ensaio impacta diretamente na interpretação dos resultados de ensaios em engenharia. A literatura recente recomenda, em alguns casos, a determinação da incerteza de medição através do Método de Monte Carlo (MMC), que considera a propagação da distribuição ao invés da propagação das incertezas. Assim, esse trabalho tem como objetivo implementar o cálculo da incerteza para o ensaio de tenacidade à fratura K_{IC} de materiais metálicos através do Método de Monte Carlo. Os resultados do trabalho confirmam a importância da estimativa da incerteza de medição de ensaios de tenacidade à fratura.

Palavras-chave: Monte Carlo, incerteza de medição, tenacidade à fratura K_{IC}.

Abstract: The estimation of the measurement uncertainty in testing laboratories has a direct impact on the interpretation of the results in the field of engineering. In some cases, recent literature recommends measurement uncertainty to be determined by the Monte Carlo Method (MCM), which considers the propagation of the distribution rather than the propagation of uncertainties. Thus, this work aims to implement the measurement uncertainty estimation for the plane-strain fracture toughness K_{IC} test of metallic materials through the Monte Carlo Method. The results of the work confirm the importance of estimating the measurement uncertainty of fracture toughness tests.

Keywords: Monte Carlo, measurement uncertainty, plane-strain fracture toughness K_{IC}.

1. INTRODUCTION

The correct expression of measurement uncertainty by test laboratories is considered a fundamental factor, since it has a direct impact on the interpretation of the results [1], and is required by the ISO/IEC 17025 standard. The Guide to Expression of Uncertainty in Measurement (GUM) is a document that establishes the criteria for calculation and expression of measurement uncertainty, considering the different influences of each parameter that composes the uncertainty value [2]. For cases where the description of the mathematical function considering each source of uncertainty is difficult, it is recommended that measurement uncertainty be determined by other mathematical methods, such as the Monte Carlo Method. Supplement 1 of GUM shows each of the steps for determining measurement uncertainty by this method [3].

Fracture toughness tests evaluate the strength of the material in front of a crack. The goal of Fracture Mechanics is to determine if a defect will or not lead a component to catastrophic fracture at normal service tension, also allowing determining the degree of safety of a cracked component [4].

In metallurgical testing, it is import to obtain fracture toughness properties, because the oil & gas industries require high performance materials. Therefore, for this application, it is indispensable to know the plane-strain fracture toughness (K_{IC}) value of materials [5].

In order to obtain the K_{IC} value of the material from mechanical testing, a provisional value, named K_Q, is initially calculated as a function that depends on the span (S) between the external loading points on the three-point test specimens, the applied load (P_Q), the specimen thickness (B), the initial crack size (a) and f, a dimensionless function of a/W, where W represents the specimen width. This ratio is given in Equation 1, according to ASTM E399-12e3 standard [6].

$$K_Q = S\frac{P_Q}{BW^{3/2}}f\left(\frac{a}{W}\right) \qquad (1)$$

The Monte Carlo Method can be described as a statistical method in which a random number sequence is used to perform a simulation [7] or an artificial sampling method that numerically operates complex systems with independent input quantities [8].

Some typical situations in which the GUM Supplement 1, which uses the Monte Carlo Method, is especially indicated for the uncertainty calculation are: The contributory uncertainties are not of approximately the same magnitude; it is difficult or inconvenient to provide the partial derivatives of the model, as needed by the law of propagation of uncertainty; the probability density function (PDF) for the output quantity is not a Gaussian distribution; an estimate of the output quantity and the associated standard uncertainty are approximately of the same magnitude; the models are arbitrarily complicated; the PDFs for the input quantities are asymmetric [3].

Given the limitations of the GUM method, especially its restriction for measurement models with a high degree of non-linearity or complexity (as is the case of the K_{IC} test measurement model), this work has as main goal to implement the calculation of measurement uncertainty for the plane-strain fracture toughness K_{IC} test through Monte Carlo simulation.

2. MATHERIAL AND METHOD

Three point bend test specimens (SEB) of base material obtained from R350HT high-strength rails were tested, according to EN 13674-1 standard [9]. The specimens were obtained from three railroad segments, i.e., from three runs, named runs I, II and III, with three samples for each run, totaling nine test specimens. The specimens were removed from the railhead indicated by EN 13674-1.

Test temperature was set to (-20 ± 1) ºC, obtained through dry ice and alcohol, controlled and monitored by a thermocouple located in the test specimens. Tests were performed in a universal electromechanical test machine with a capacity of 250 KN. The fatigue pre-cracks were opened with a 100 KN servo-hydraulic test machine. Tests were performed based on standards EN 13674-1 (product standard) and ASTM E399 (test standard).

For the measurement uncertainty calculation by the Monte Carlo method, at first, a spreadsheet considering GUM Supplement 1 was built through Crystal Ball® software, applying the K_{IC} measurement model (Equation 1).

According to Herrador and González [10], Crystal Ball® is a user-friendly and customizable Excel add-in that easily enables Monte Carlo simulations to be performed. The measurement uncertainty calculation procedure was implemented at a 95.45% coverage probability using 1,000,000 iterations for each simulation.

3. RESULTS AND DISCUSSION

From the K_Q measurement model (1), uncertainty sources for the test were identified. It is important to notice that, when de K_Q calculated value is validated, K_Q is considered equal to K_{IC}.

Input quantities *S*, *B* and *W* from (1) are dimensional, and obtained from digital caliper measurement. The acceptance criterion of equipment calibration, which is considered as a source of uncertainty for these three variables, is ± 0.02 mm, according to normative standards for dimensional measurements. The form factor *f* (*a*/*W*) was considered, for purposes of calculation, as a constant of the material. Thus, any sources of uncertainty associated with this parameter were considered negligible. The input quantity P_Q represents a strength measure obtained from the load cell. For this equipment, the maximum acceptable error is 1% of the measured value, and this value is used as the source of uncertainty for this variable. Thus, the uncertainty sources to be considered in this work can be summarized according to Table 1.

Table 1. Uncertainty sources for K_{IC} test.

Input quantity	Uncertainty source and value	PDF
P_Q	Equipment acceptance criteria: 1%P_Q	Rectangular
S, B, W	Equipment acceptance criteria: 0.02 mm	Rectangular

The probability distribution related to each uncertainty source is a difficult parameter to estimate. In this work, probability distribution for input values will be considered uniform (rectangular), which is the most severe situation.

The software allows obtaining the coverage interval through the required percentiles (in this case, 2.275% and 97.725%) for the measurement uncertainty calculation, but also allows obtaining many other statistical values, such as average, standard deviation, among others. From the percentiles obtained, the uncertainty can be calculated according to (2).

$$U = \frac{\text{Percentile}_{97.725\%} - \text{Percentile}_{2.275\%}}{2} \qquad (2)$$

The calculated values of K_{IC} and their measurement uncertainty are shown in Table 2.

As shown in Table 2, measurement uncertainty values are different among them. However, when the measured values are observed within the same run, the values seem close to each other, with a smaller standard deviation.

Table 2. Test results.

Run / Specimen	$K_{IC} = K_Q$ [MPa.m$^{1/2}$]	Uncertainty [MPa.m$^{1/2}$]
I-1	40.17	0.39
I-2	41.87	0.40
I-3	42.27	0.41
II-1	33.35	0.32
II-2	34.02	0.33
II-3	32.64	0.31
III-1	33.38	0.32
III-2	33.11	0.32
III-3	34.17	0.33

The calculated measurement uncertainty values are about 1% of the K_{IC} values. There is no description of maximum/minimum uncertainty values accepted by the fracture toughness test standard, but it specifies an acceptance criterion for the material K_{IC}. For R350HT high-strength rails, the minimum acceptable K_{IC} is 30 MPa.m$^{1/2}$ [9]. The K_{IC} measured values were above this specification and, furthermore, since the measurement uncertainty values were small, no 'false positives' were generated in the interpretation of this specification. For several mechanical tests, such as Brinell hardness, Rockwell hardness and tension testing, a proportional value of measurement uncertainty at 1% is considerably accepted [11].

4. CONCLUSION

This work demonstrated that the adaptation and use of the Monte Carlo Method to calculate the measurement uncertainty for the plane-strain fracture toughness K_{IC} test of metallic materials was adequate and important to overcome limitations of other methods for uncertainty estimation. The importance of MCM is emphasized because it is easy to associate the probability distribution of the different sources of uncertainty considered, which is not allowed by the GUM.

The measurement uncertainty values obtained were small, about 1% of the K_{IC} values, and the K_{IC} values considering the measurement uncertainty were within the material acceptance criterion. This result is considered satisfactory.

5. REFERENCES

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