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USE OF POOLED STANDARD DEVIATION TAKEN FROM HISTORICAL DATA IN CALCULATING THE MEASUREMENT UNCERTAINTY IN TENSILE TESTS

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Abstract: The specification of mechanical properties is essential for adequate choice of material, as well as for design and manufacturing of components and products. It is recognised that the present state of uncertainties application in testing activities is not as comprehensive as in the calibration fields. This paper presents guidelines for the calculation of measurement uncertainty in tensile tests (tensile strength and percentage elongation after fracture), making the type A evaluation from historical data. And it is also demonstrated that the application of strength standard deviation has larger representativeness than the use of diameter and load standard deviations.

Keywords: measurement uncertainty, tensile test, Type A evaluation, historical data.

1. INTRODUCTION

With the edition of the ISO GUM [1], the measurement uncertainty has often been used in the measurement results, especially in the calibration field. ISO 17025:2005 [2] makes clear the need to calculate and express the measurement uncertainty in the calibration results.

The International Vocabulary of Metrology - VIM [3] defines the measurement result as "a set of quantity values being attributed to a measurand together with any other available relevant information. A measurement result is generally expressed as a single measured quantity value and a measurement uncertainty". As a result of measurement represents the true value of the measurand, uncertainty becomes necessary to express the doubt associated with this result.

Measurement uncertainty is a non-negative parameter characterizing the dispersion of the quantity values being attributed to the measurand [3]. According to the ISO GUM [1], many commercial, industrial, health and safety applications need to know the interval about the measurement result that can reasonably be attributed to the measurand.

The specification of mechanical properties is essential for the adequate choice of material, as well as for the design and manufacturing of components and products. The mechanical properties define the behaviour of the material when subjected to mechanical stress, because they are related to the material's ability to resist or transmit these applied efforts without breaking and without deform uncontrollably [4].

It is recognised that the present state of development and application of uncertainties in testing activities is not as comprehensive as in the calibration fields. It is therefore accepted that the implementation of ISO/IEC 17025:2005 criteria on this subject will take place at an appropriate pace, which may differ from one field to another. However laboratories should be able to satisfy requests from clients, or requirements of specifications, to provide statements of uncertainty [5].

The reference standard for performing tensile tests on metals at room temperature, ISO 6892-1: 2009 [6], states that measurement uncertainty analysis is useful for identifying major sources of inconsistencies of measured results. But also describes that it is not possible to give an absolute statement of uncertainty for this method, because the contribution of the tested material. In an analysis of historical data from tests on different materials, Domeneghetti [7] found a significant difference in repeatability, as shown in Fig. 1.

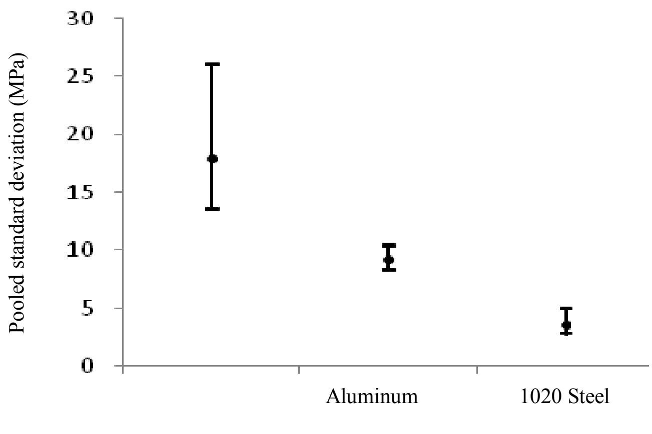

Fig. 1. Comparison of the confidence interval (95%) of the pooled standard deviation for the tensile strength

Different papers, with different approaches, provide guidelines for the estimation of measurement uncertainty in tensile testing, like Silva [8], Restivo e Sousa [9], Gupta [10], Gabauer [11], Adams [12], Aydemir [13], as also ISO 6892-1: 2009 [6].

The inability to perform tensile tests on larger sample sizes, because of cost and time associated, may make impracticable the expression of measurement uncertainty in some test results.

Other topic noted in the evaluation of measurement uncertainty for tensile strength is the use of separate values for the standard uncertainty of load and area. Given that different measures can be obtained in the manufacture of the standard tensile specimen, calculating the standard deviation of these measures will impact differently on the results.

The objective of this paper is to present guidelines for the calculation of measurement uncertainty of tensile tests (tensile strength and percentage elongation after fracture), making the Type A evaluation from historical data.

Although the aims of this paper are tensile tests, it should be noted that the methodology is not restricted only to those. It can be applied to a wide range of physic-chemical analysis, environmental analysis, micrographic and macrographic analysis, non destructive testing, and others required by the industrial sector.

2. GENERAL GUIDELINES OF ISO GUM

The Guide to Expression of Uncertainty in Measurement - ISO GUM provides general rules for evaluating and expressing measurement uncertainty, which can be followed at various levels of accuracy and in many fields, from shop floor to fundamental research. The guidelines are specified in ISO GUM [1], and are available on the BIPM website.

Only a brief approach of estimating the standard uncertainty by the Type A evaluation of uncertainty is made in this paper. The Type A evaluating method uses statistical procedures and can be applied when J observations have been made independent of the input quantities under the same measuring conditions. The standard uncertainty associated with this estimate is given, often by the average standard deviation:

$$u(x_i) = s(\overline{x_i}) = \frac{s(x_i)}{\sqrt{J}} \quad (1)$$

where $s(x_i)$ is experimental standard deviation, calculated from the number of observations x_{ij}:

$$s(x_i) = \sqrt{\frac{1}{J-1}\sum_{j=1}^{J}(x_{ij}-\overline{x}_i)^2} \quad (2)$$

The degrees of freedom υ_i associated with this standard uncertainty are determined from a *t* distribution, where $\upsilon_i = J - 1$.

Considering the small size samples, as most of the mechanical tests, it is possible to determine the standard uncertainty through pooled standard deviation from several batches or samples, which is determined by the following equation:

$$s_{pooled} = \sqrt{\frac{1}{N-K}\sum_{i=1}^{N}(n_i - 1).s_i^2} \quad (3)$$

where:

s_{pooled} = pooled standard deviation
s = standard deviation for each sample
n = number of measurements per sample
N = total of measurements
K = number of samples

The use of pooled standard deviation allows the use of smaller samples, without compromising the degree of freedom associated with the respective standard uncertainty.

3. TENSILE TEST

This paper will assess the uncertainties related to the parameters: tensile strength and percentage elongation after fracture.

The results of the tensile test are influenced by factors related to the material, specimen, test equipment, test procedure and calculation of mechanical properties. These factors are confirmed by Silva [8], which influences are classified into two categories: metrological parameters and material and testing parameters.

3.1 TENSILE STRENGTH

According ISO 6892-1:2009 [6], tensile strength is defined as the stress corresponding to the maximum force.

The mathematical model for the tensile strength (Rm) can be summarized as a function of the repeatability and measuring equipments:

$$Rm = f\,(D, F, B_M, L_M, B_C, L_C) \quad (4)$$

where:

D = Original external diameter of test piece
F = Maximum force
B_M = Bias of testing machine
L_M = Testing machine resolution
B_C = Bias of caliper
L_C = Caliper resolution

In general, tensile strength is calculated from the uncorrected values of force and diameter test piece experimentally obtained:

$$\sigma = \frac{4F}{\pi D^2} \quad (5)$$

Considering the factors of influence reported in the mathematical expression (Eq. 4), the tensile strength, represented by the ratio between load and area, is given by:

$$Rm = 4\ \frac{F - B_M - L_M}{\pi(D - B_C - L_C)^2} \quad (6)$$

Replacing the relationship given by Eq. (5) in Eq. (6), it is obtained the mathematical expression for tensile strength:

$$Rm = \frac{D^2\sigma}{(D - B_C - L_C)^2} - \frac{4\ BM}{\pi(D - B_C - L_C)^2}\frac{4\ REM}{\pi(D - B_C - L_C)^2} \quad (7)$$

With the mathematical model presented in Eq. (7), it is possible to identify the influence of different components on the measurement results and to calculate the sensitivity coefficients. From the expression (7) are obtained sensitivity coefficients for the experimental tensile strength (σ), diameter (D), machine (M), caliper (C), respectively:

$$c_\sigma = \frac{D^2}{(D-B_C-L_C)^2} \qquad (8)$$

$$c_D = \frac{2DT}{(D-B_C-L_C)^2} - \frac{2\pi D^2\sigma - 8B_M - 8L_M}{\pi(D-B_C-L_C)^3} \qquad (9)$$

$$c_M = \frac{-4}{\pi(D-B_C-L_C)^2} \qquad (10)$$

$$c_C = \frac{2\pi D^2\sigma - 8B_M - 8L_M}{\pi(D-B_C-L_C)^3} \qquad (11)$$

By assigning correction values equal to zero, the above expressions can be simplified:

$$c_\sigma = 1 \qquad (12)$$

$$c_D = 0 \qquad (13)$$

$$c_M = \frac{-4}{\pi D^2} \qquad (14)$$

$$c_C = \frac{2\sigma}{D} \qquad (15)$$

3.2 PERCENTAGE ELONGATION AFTER FRACTURE

According ISO 6892-1:2009 [6], percentage elongation after fracture is define as the permanent elongation of the gauge length after fracture, expressed as a percentage of the original gauge length.

The mathematical model for percentage elongation after fracture (A) can be summarized as a function of the repeatability and measuring equipments:

$$A = f\,(L_o, L_u, B_C, L_C) \qquad (16)$$

where:

L_o = original gauge length
L_u = final gauge length after rupture
B_C = Bias of caliper
L_C = Caliper resolution

In general, percentage elongation after fracture is calculated from the uncorrected values of original and final gauge length experimentally obtained:

$$\varepsilon = 100\frac{(L_u-L_o)}{L_o} = 100\frac{\Delta L}{L_o} \qquad (17)$$

Considering the factors of influence reported in the mathematical expression (Eq. 16), percentage elongation after fracture, represented by the ratio between elongation and original length, is given by:

$$A = 100\frac{(L_u-L_o)}{(L_o-B_C-L_C)} = 100\frac{\Delta L}{(L_o-B_C-L_C)} \qquad (18)$$

In the Eq. (18) are not pointed out caliper corrections to calculate ΔL, because the systematic effect is cancelled. However, its random effect should be considered in the measurement uncertainty estimation.

Replacing the relationship given by Eq. (17) in Eq. (18), it is obtained the mathematical expression for percentage elongation after fracture:

$$A = \frac{\varepsilon\, L_o}{L_o-B_C-L_C} \qquad (19)$$

With the mathematical model presented in Eq. (19), it is possible to identify the influence of different components on the measurement results and to calculate the sensitivity coefficients. To simplify the sensitivity coefficients obtained from Eq. (19), it is attributed value zero for Bias and for resolution systematic effect. Sensitivity coefficients for the experimental percentage elongation after fracture (ε) and caliper (C) are, respectively:

$$c_\varepsilon = 1 \qquad (20)$$

$$c_{C_o} = \frac{100}{L_o} + \frac{E}{L_0} \qquad (21)$$

$$c_{C_u} = -\frac{100}{L_0} \qquad (22)$$

The caliper sensitivity coefficients are related to original and final gauge length measured, respectively.

4. EXPERIMENTAL PROCEDURES AND RESULTS

An experiment was conducted to evaluate measurement results of the tensile test, composed of seven samples of three test pieces, all obtained from the same 1020 Steel bar. Table 1 lists the standard deviations obtained for diameter, load, final gauge length after rupture, tensile strength and percentage elongation after rupture.

Table 1. Experimental standard deviation

Sample	D (mm)	F (N)	L_u (mm)	σ (MPa)	ε (%)
1	0,0000	174,94	0,0404	1,155	0,058
2	**0,0231**	**227,60**	**0,9322**	2,082	**1,332**
3	**0,0058**	**56,00**	**0,3156**	0,000	**0,451**
4	0,0153	205,58	0,3453	2,082	0,493
5	0,0115	322,67	0,2524	2,000	0,361
6	0,0100	54,00	0,4200	1,000	0,600
7	0,0232	333,04	0,5658	2,082	0,808
Pooled standard deviation	**0,015**	**222,2**	**0,485**	**1,66**	**0,69**

Samples 2 and 3 were considered for the results compilation, because they had different standard deviations.

Original gauge length of the test piece was 70 mm. Other original data are given in Table 2.

Table 2. Original data for Sample 2 and Sample 3

Sample	D (mm)	F (N)	L_u (mm)	σ (MPa)	ε (%)
2	13,91	67928	94,43	447	34,9
	13,91	67473	93,87	444	34,1
	13,87	67689	92,61	448	32,3
Average	13,897	67696,7	93,637	446,33	33,77
3	13,83	67149	93,1	447	33
	13,84	67246	93,45	447	33,5
	13,84	67246	92,82	447	32,6
Average	13,837	67213,7	93,123	447,00	33,03

Expanded uncertainties associated to testing machine and caliper were taken from calibration certificates, 370 N and 0,01 mm, respectively. Both results with k = 2.

4.1 TENSILE STRENGTH

For each sample, three situations calculation were performed:

- Distinct Type A evaluating for diameter and force (Fig. 2 and Fig. 3);

Source of Uncertainty	$u(x_i)$	Distrib.	c_i	$u_i(y)$ (MPa)	v_i/veff
Force Repeatibility (N)	131,4	t	0,0066	0,87	2
Machine Uncertainty (N)	185,0	N	0,0066	1,22	∞
Machine Resolution (N)	5,8	R	0,0066	0,04	∞
Diameter Repeatibility (mm)	0,013	t	64,236	0,86	2
Caliper Uncertainty (mm)	0,005	N	64,236	0,32	∞
Caliper Resolution (mm)	0,006	R	64,236	0,37	∞
	Combined uncertainty u(y) - MPa			1,79	18
	Expanded uncertainty U - MPa			3,9	
		k (P ~ 95%)		2,15	

Fig. 2. Expanded Uncertainty for Sample 2, considering distinct Type A evaluating for diameter and force

Source of Uncertainty	$u(x_i)$	Distrib.	c_i	$u_i(y)$ (MPa)	v_i/veff
Force Repeatibility (N)	32,3	t	0,0066	0,21	2
Machine Uncertainty (N)	185,0	N	0,0066	1,23	∞
Machine Resolution (N)	5,8	R	0,0066	0,04	∞
Diameter Repeatibility (mm)	0,003	t	64,610	0,22	2
Caliper Uncertainty (mm)	0,005	N	64,610	0,32	∞
Caliper Resolution (mm)	0,006	R	64,610	0,37	∞
	Combined uncertainty u(y) - MPa			1,36	> 50
	Expanded Uncertainty U - MPa			2,7	
		k (P ~ 95%)		2,00	

Fig.3. Expanded Uncertainty for Sample 3, considering distinct Type A evaluating for diameter and force

- Tensile strength standard deviation obtained from the sample itself (Fig. 4 and Fig. 5):

Source of Uncertainty	$u(x_i)$	Distrib.	c_i	$u_i(y)$ (MPa)	v_i/veff
Tensile Strength Repeatibility (MPa)	1,20	t	1	1,20	2
Machine Uncertainty (N)	185	N	0,0066	1,22	∞
Machine Resolution (N)	5,8	R	0,0066	0,04	∞
Caliper Uncertainty (mm)	0,005	N	64,610	0,32	∞
Caliper Resolution (mm)	0,006	R	64,610	0,37	∞
			u(y) - MPa	1,79	9
			U - MPa	4,1	
			k (P ~ 95%)	2,32	

Fig. 4. Expanded Uncertainty for Sample 2, considering standard deviation obtained from the sample itself

Source of Uncertainty	$u(x_i)$	Distrib.	c_i	$u_i(y)$ (MPa)	v_i/veff
Tensile Strength Repeatibility (MPa)	0,00	t	1	0,00	2
Machine Uncertainty (N)	185	N	0,0066	1,22	∞
Machine Resolution (N)	5,8	R	0,0066	0,04	∞
Caliper Uncertainty (mm)	0,005	N	64,236	0,32	∞
Caliper Resolution (mm)	0,006	R	64,236	0,32	∞
			u(y) - MPa	1,33	> 50
			U - MPa	2,7	
			k (P ~ 95%)	2,00	

Fig. 5. Expanded Uncertainty for Sample 3, considering standard deviation obtained from the sample itself

- Pooled standard deviation for tensile strength (Fig.6 and Fig. 7).

Source of Uncertainty	$u(x_i)$	Distrib.	c_i	$u_i(y)$ (MPa)	v_i/veff
Tensile Strength Repeatibility (MPa)	0,96	t	1	0,96	14
Machine Uncertainty (N)	185	N	0,0066	1,22	∞
Machine Resolution (N)	5,8	R	0,0066	0,04	∞
Caliper Uncertainty (mm)	0,005	N	64,236	0,32	∞
Caliper Resolution (mm)	0,006	R	64,236	0,37	∞
			u(y) - MPa	1,63	>50
			U - MPa	3,3	
			k (P ~ 95%)	2,00	

Fig. 6. Expanded Uncertainty for Sample 2, considering pooled standard deviation

Source of Uncertainty	$u(x_i)$	Distrib.	c_i	$u_i(y)$ (MPa)	v_i/veff
Tensile Strength Repeatibility (MPa)	0,96	t	1	0,96	14
Machine Uncertainty (N)	185	N	0,0066	1,22	∞
Machine Resolution (N)	5,8	R	0,0066	0,04	∞
Caliper Uncertainty (mm)	0,005	N	64,610	0,32	∞
Caliper Resolution (mm)	0,006	R	64,610	0,37	∞
			u(y) - MPa	1,64	>50
			U - MPa	3,3	
			k (P ~ 95%)	2,00	

Fig. 7. Expanded Uncertainty for Sample 3, considering pooled standard deviation

In summarized form, Table 3 shows the expanded uncertainties for three situations performed:

Table 3. Expanded Uncertainty for Tensile Strength (in MPa)

Situation	Minimum	Maximum
Distinct Type A evaluating for diameter and force	2,7	3,9
Tensile strength standard deviation obtained from the sample itself	2,7	4,1
Pooled standard deviation for tensile strength	3,3	3,3

Based on the accomplished calculations, it is observed that the sample size is meaningful in the measurement result.

4.2 PERCENTAGE ELONGATION AFTER FRACTURE

To evaluate the percentage elongation after fracture measurement uncertainty, three situations were considered for each sample:

- Distinct Type A evaluating for L_o and L_u (Fig. 8 and Fig. 9);

Source of Uncertainty	$u(x_i)$	Distrib.	c_i	$u_i(y)$ (%)	v_i/veff
Lo Repeatibility (mm)	0,029	R	1,911	0,055	∞
Caliper Uncertainty for Lo (mm)	0,005	N	1,911	0,010	∞
Caliper Resolution for Lo (mm)	0,006	R	1,911	0,011	∞
Lf Repeatibility(mm)	0,539	t	1,429	0,769	2
Caliper Uncertainty for Lf (mm)	0,005	N	1,429	0,007	∞
Caliper Resolution for Lf (mm)	0,006	R	1,429	0,008	∞
	Combined uncertainty u(y) - %			0,772	2
	Expanded uncertainty U - %			3,5	
			k (P ~ 95%)	4,53	

Fig. 8. Expanded Uncertainty for Sample 2, considering distinct Type A evaluating for L_o and L_u

Source of Uncertainty	$u(x_i)$	Distrib.	c_i	$u_i(y)$ (%)	v_i/veff
Lo Repeatibility (mm)	0,029	R	1,910	0,055	∞
Caliper Uncertainty for Lo (mm)	0,005	N	1,910	0,010	∞
Caliper Resolution for Lo (mm)	0,006	R	1,910	0,011	∞
Lf Repeatibility(mm)	0,182	t	1,429	0,260	2
Caliper Uncertainty for Lf (mm)	0,005	N	1,429	0,007	∞
Caliper Resolution for Lf (mm)	0,006	R	1,429	0,008	∞
	Combined uncertainty u(y) - %			0,262	2
	Expanded uncertainty U - %			1,2	
			k (P ~ 95%)	4,53	

Fig.9. Expanded Uncertainty for Sample 3, considering distinct Type A evaluating for L_o and L_u

- Elongation standard deviation obtained from the sample itself (Fig. 10 and Fig. 11):

Source of Uncertainty	$u(x_i)$	Distrib.	c_i	$u_i(y)$ (%)	v_i/veff
Elongation Repeatibility (%)	0,769	t	1	0,769	2
Caliper U for Lo (mm)	0,005	N	1,911	0,010	∞
Caliper R for Lo (mm)	0,006	R	1,911	0,011	∞
Caliper U for Lf (mm)	0,005	N	1,429	0,007	∞
Caliper R for Lf (mm)	0,006	R	1,429	0,008	∞
			u(y) - %	0,769	2
			U - %	3,5	
			k (P ~ 95%)	4,53	

Fig. 10. Expanded Uncertainty for Sample 2, considering standard deviation obtained from the sample itself

Source of Uncertainty	$u(x_i)$	Distrib.	c_i	$u_i(y)$ (%)	v_i/veff
Elongation Repeatibility (%)	0,260	t	1,910	0,260	2
Caliper U for Lo (mm)	0,005	N	1,910	0,010	∞
Caliper R for Lo (mm)	0,006	R	1,910	0,011	∞
Caliper U for Lf (mm)	0,005	N	1,429	0,007	∞
Caliper R for Lf (mm)	0,006	R	1,429	0,008	∞
			u(y) - %	0,261	2
			U - %	1,2	
			k (P ~ 95%)	4,53	

Fig. 11. Expanded Uncertainty for Sample 3, considering standard deviation obtained from the sample itself

- Pooled standard deviation for elongation (Fig.12 and Fig. 13).

Source of Uncertainty	$u(x_i)$	Distrib.	c_i	$u_i(y)$ (%)	v_i/veff
Elongation Repeatibility (%)	0,400	t	1	0,400	14
Caliper U for Lo (mm)	0,005	N	1,911	0,010	∞
Caliper R for Lo (mm)	0,006	R	1,911	0,011	∞
Caliper U for Lf (mm)	0,005	N	1,429	0,007	∞
Caliper R for Lf (mm)	0,006	R	1,429	0,008	∞
			u(y) - %	0,401	14
			U - %	0,9	
			k (P ~ 95%)	2,20	

Fig. 12. Expanded Uncertainty for Sample 2, considering pooled standard deviation

Source of Uncertainty	$u(x_i)$	Distrib.	c_i	$u_i(y)$ (%)	v_i/veff
Elongation Repeatibility (%)	0,400	t	1,910	0,400	14
Caliper U for Lo (mm)	0,005	N	1,910	0,010	∞
Caliper R for Lo (mm)	0,006	R	1,910	0,011	∞
Caliper U for Lf (mm)	0,005	N	1,429	0,007	∞
Caliper R for Lf (mm)	0,006	R	1,429	0,008	∞
			u(y) - %	0,401	14
			U - %	0,9	
			k (P ~ 95%)	2,20	

Fig. 13. Expanded Uncertainty for Sample 3, considering pooled standard deviation

In summarized form, Table 4 shows the expanded uncertainties for three situations performed:

Table 4. Expanded Uncertainty for Percentage Elongation (in %)

Situation	Minimum	Maximum
Distinct Type A evaluating for L_o and L_u	1,2	3,5
Elongation standard deviation obtained from the sample itself	1,2	3,5
Pooled standard deviation for elongation	0,9	0,9

In evaluating the measurement uncertainty of the percentage elongation after rupture, it is observed that the dominant component variation is obtained by type A evaluation. In this case, a larger number of degrees of freedom is necessary to better estimate the repeatability standard uncertainty. As the sample size is small, it is recommended to use the pooled standard deviation from more samples.

5. CONCLUSIONS

It is common that small samples are applied in the accomplishment of the mechanical tests, that will affect the determination of the repeatability standard deviation. Through the obtained results, it was also verified that the factor of larger influence in the uncertainty calculation for the tensile strength and for percentage elongation after rupture is the measuring dispersion. In this case, historical data become a viable alternative to be used for estimate the repeatability standard deviation. However, it is important to detach that the use of historical data is for material type that is being analyzed, equipment model and test method. However, it is evident that the pooled standard deviation is a viable and justifiable solution to represent the standard uncertainty determined by Type A evaluation.

The used methodology provides subsidies to the laboratories and companies implement the measurement uncertainty calculation in tests area, presenting complete measurement results and improved reliability.

This paper is indicated to guide laboratories that supply test results and for companies that use these results for making decisions.

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