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ASSESSMENT OF UNCERTAINTY ASSOCIATED WITH YIELD STRENGTH OBTAINED ACCORDING TO ASTM E8/E8M STANDARD

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Abstract. *This work aims to evaluate the uncertainty associated with the yield strength of AISI 4340 steel (28 HRC) obtained in accordance with the ASTM E8/E8M standard (ASTM, 2022). In order to popularize the uncertainty calculation associated with this mechanical property, the developed methodology, rooted in the GUM method (Guide to the expression of uncertainty in measurement), was implemented in MATLAB® R2019a and validated. The expanded uncertainty associated with the yield strength, determined through tensile tests for a single specimen was 2.25 MPa, representing 0.3 % of the average (770.47 MPa). The yield strength value resulting from the tensile test of AISI 4340 steel considering three specimens was 776.99 ± 4.90 MPa. The expanded uncertainty, in this case, represents 0.6 % of the average yield strength value. The code developed in MATLAB®R2019a allowed to determine the uncertainty associated with the yield strength in an adequate way. This code makes it possible to popularize the calculation of the uncertainty associated with this important mechanical property. Furthermore, it can serve as a basis (with adaptations) to calculate the uncertainty associated with other measurands.*

Keywords: *Measurement Uncertainty, Yield Strength, GUM.*

1. INTRODUCTION

Good practice in measuring mechanical properties of engineering materials is to evaluate and report the associated uncertainties. An uncertainty statement may be required by a customer who wants to know the limits within which the reported result may fall. Additionally, the test laboratory itself may wish to have a better understanding of which specific aspects of the test procedure and measurement system have the greatest effect on results (Gabauer, 2000) so that strategies can be adopted, and these effects eliminated or reduced.

The tensile test is used to assess the strength and ductility of metals and alloys. In this test, a metal specimen is stretched to failure in a relatively short time at a constant strain rate determined by standards, such as ASTM E8/E8M (ASTM, 2022). The mechanical properties of metals and alloys that are of importance for the design of mechanical components or engineering structures can be obtained from the tensile test, such as modulus of elasticity, yield strength, ultimate tensile stress, total elongation and reduction in area. Most mechanical components and engineering structures are designed so that during service loads, only elastic deformations occur (with the exception, for example, of structures for shock absorption). Although, safety factors are applied in mechanical and structural designs, it is still of great importance to know the yield stress level and the associated uncertainties, because from this, permanent plastic deformations occur, which can lead to loss of function or even component, equipment or structure to failure.

According to ASTM E8/E8M (ASTM, 2022), the yield strength measurement is the value of the stress at which, after releasing the force, a residual plastic deformation remains, whose value depends on the material, as exemplified in Figure 1a, for the case of material does not show the occurrence of a deformation plateau. In this case, a value of residual plastic deformation, *m*, is adopted, whose value can vary from 0.2 % to 2.0 %. There is also the case of materials that present the clear flow region, Figure 1b. Regardless of the case (material) the determination of the ultimate yield stress value and its uncertainty must comply with well-established rules and criteria.

Gabauer (2000) proposed a procedure for uncertainty evaluation in tensile test results obtained from tests at ambient or elevated temperature, carried out according to EN 10002-Part 1 (EN, 1990), EN 10002-Part 5 (EN, 1990), ASTM E8 (ASTM, 1998) and ASTM E111 (ASTM, 1997). This procedure was based on GUM method (Guide to the expression of

uncertainty in measurement). Nevertheless, most tensile test results lack a statement of the associated measurement uncertainty.
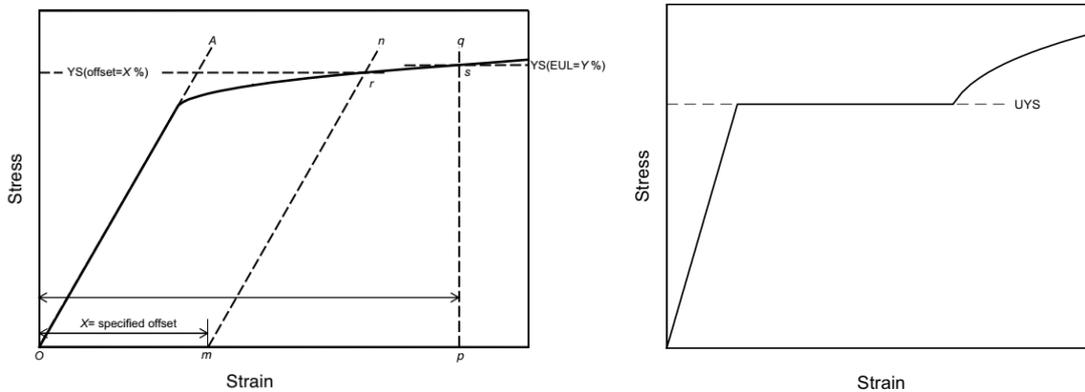

Figure 1. Stress-Strain diagram for determination of yield strength by the offset and extension-under-load methods. Stress-Strain diagram showing upper yield strength corresponding with top of knee.

Error calculations in scientific works that deal with the subject of determination of physical quantities considered as material characteristic are difficult to find. The author justified this fact by three main factors: the error analysis is based on detailed calculations in the area of differential calculus, the calculations are time-consuming and laborious (GRABA, 2021). Added to these factors is the lack of metrological culture and the difficulty of GUM understanding and applying This is the main method when it comes to evaluating measurement uncertainties. Thus, this work aims to evaluate the uncertainty associated with the yield strength obtained in accordance with the ASTM E8/E8M (ASTM, 2022). In order to popularize the uncertainty calculation associated with this mechanical property, the developed methodology, based on the GUM method, was implemented in MATLAB® R2019a and validated.

Xu et al., (2021) proposed a new technology system for tensile testing is proposed by using a curve of "mechanical property−tensile strain rate" at a given temperature. This technology was based on the elastic deformation mechanism of the measurement uncertainty of tensile testing results, and aimed to characterize the original mechanical property, the service mechanical property, and the mechanical property during processing deformation.

2. METHODOLOGY

The yield strength of three specimens of AISI 4340 steel (28 HRC) was determined through tensile tests, conducted in accordance with ASTM E8/E8M (ASTM, 2022). Figure 2 shows the geometry and dimensions of the specimens tested for this purpose.
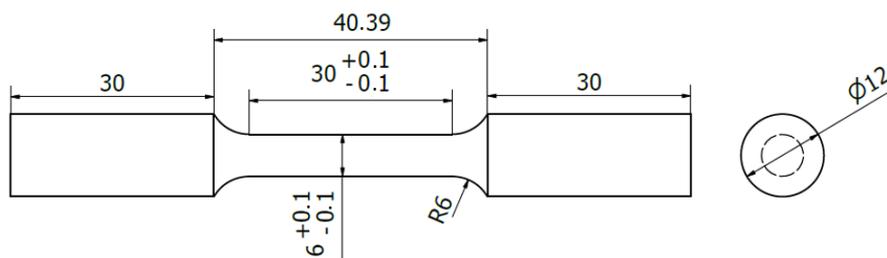

Figure 2. Geometry and dimensions of the specimen for the tensile test (ASTM E8/E8M, 2016).

The specimens were machined using a computer numerical control (CNC) lathe Romi model GL 240M. Following the machining process, the reduced diameter section of each specimen was measured at three positions along its length. For this purpose, a digital caliper from the manufacturer Mitutoyo with a resolution of 0.01 mm and a nominal range of 150 mm was used. The expanded uncertainty associated with caliper calibration is 0.01 mm for external measurements.

The tensile tests were conducted using an Instron® universal machine manufacturer model 8801, with a nominal range of ±100 kN. The calibration certificate for the Instron® universal testing machine specifies an expanded uncertainty of 0.09 kN for a coverage probability of 95 % within the force range of 22.4745 kN to 100.1324 kN. Tensile tests were carried out under displacement control with speeds of 0.48 mm/min up to 4 % deformation and 2 mm/min for the

remainder of the test. The deformation within the elastic region was measured using an axial electromechanical strain gauge from Instron®, model 2620-601, with a nominal range of ± 5 mm and a resolution of 0.01 µm. The calibration certificate indicates an uncertainty associated with the load cell calibration of 0.09 kN, for a coverage factor (k) of 2.00 and a coverage probability of 95 %. Subsequently, the electromechanical extensometer was removed, and the strain continued to be measured by the RVDT (Rotary Variable Differential Transformer) with a resolution of 0.0000001° and a nominal range of ± 45° integrated into the equipment until the specimen ruptured.

2.1 Assessment of measurement uncertainty associated with yield strength

To evaluate the measurement uncertainty associated with yield strength the GUM method, proposed in JCGM 100:2008 (BIPM et al., 2008) was utilized. Initially, all influencing factors (input variables) that may impact the measurand values were identified. Figure 3 shows the primary factors that must be taken into consideration in determining the uncertainty associated with the yield strength obtained through the tensile test. It is evident that there are two main factors (specimen and test), to which other secondary factors are linked, namely, the specimen diameter, the circular area and the flow force. Furthermore, an additional 10 factors are associated with these secondary factors.
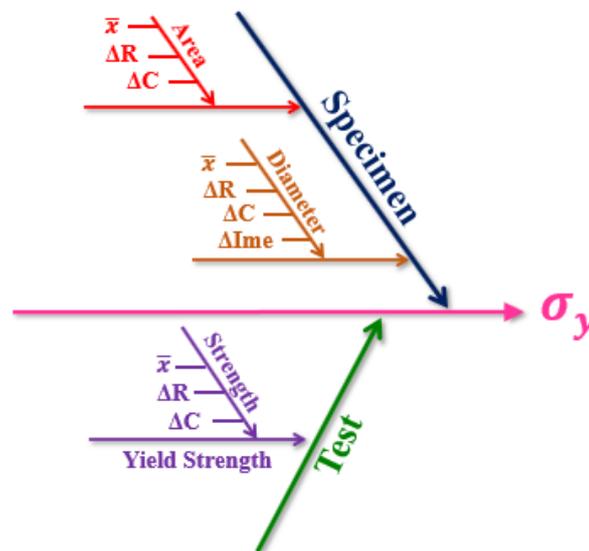

Figure 3. Ishikawa diagram with influence factors associated with yield strength.

For the purposes of calculating the uncertainty associated with the yield strength, initially, only one specimen was taken into account. This is because the uncertainty associated with determining the yield strength through tensile testing of the other specimens is calculated in a similar manner. The dimensional and geometric control of the specimen was conducted using a digital caliper specified in Table 1. This table also provides information on the measurement systems employed to assess the other measured quantities. The mathematical models utilized to evaluate the measurement uncertainty of the different measurands are also shown in Table 1.

Table 1. Measurement systems used to measure all measurands that affect the yield strength and mathematical models using during the uncertainty assessment.

Measurand	Measurement system	Mathematical models
Diameter, D	Digital caliper	$M = \bar{X} + \Delta R + \Delta C + \Delta Ime$
Area, A	Resolution: 0.01 mm Nominal range: 150 mm	$M = \dfrac{\pi \cdot D^2}{4}$
Yield strength, Fe	Instron®	$M = \bar{X} + \Delta R + \Delta C$
Yield stress, σ_y	Resolution: 0.01 kN Nominal range: ± 100 kN	$M = \dfrac{F_e}{A_n}$

In Table 1, M represents the measurand, $\bar{X}$ is the arithmetic mean of the values that were obtained during the measurement of each measurand, ΔR is the correction due to the measurement system resolution, ΔC is the correction associated with the measurement system calibration; Δlme represents the correction associated with the uncertainty of the parallelism deviation between the measurement surfaces for external measurements of the digital caliper; A is the area of the specimen used in the tensile test, and Fe is the yield strength of the specimen in the tensile test.

The uncertainty propagation law was applied in the mathematical models shown in Table 1. The results obtained after calculating the partial derivatives are presented in Table 2.

Table 2. Results of the application of the uncertainty propagation law in mathematical models.

Measurand	Results of the application of the uncertainty propagation law
Diameter, D	$u_c^2(M) = u^2(\bar{X}) + u^2(\Delta R) + u^2(\Delta C) + u^2(\Delta Ime)$
Area, A	$u_c^2(M) = \left(\frac{\pi \cdot D}{2}\right)^2 \cdot u^2(D)$
Yield strength, Fe	
Yield stress, σ_y	$u_c^2(M) = \left(\frac{F_e}{A_n}\right)^2 \cdot u^2(A_n) + \left(-\frac{F_e}{A_n^2}\right)^2 \cdot u^2(F_e)$

Table 3 shows the main information regarding the calculation of the standard uncertainty associated with the input variables.

Table 3. Summary of the information used in the calculation of the standard uncertainty associated with the input variables.

Variable	Type of assessment	Probability distribution	Effective degrees of freedom	Equation
$(\bar{X})$	Type A	T-*student*	n-1	$u(\bar{X}) = \dfrac{s(X)}{\sqrt{n}}$
ΔR	Type B	Rectangular	∞	$u(\Delta R) = \dfrac{R}{2\sqrt{3}}$
ΔC	Type B	They vary depending on the calibration certificate		$u(\Delta C) = \dfrac{U(C)}{kC}$
ΔIme	Type B			$u(\Delta Ime) = \dfrac{U(Ime)}{kIme}$

Equation (1) was used to calculate the expanded uncertainty associated with the output variable.

$$U(y) = k(y) \cdot u_c(y), \tag{1}$$

The coverage factor $k(y)$ is determined by using the Tab. G 2 of the GUM as a function of the effective degrees of freedom of the measurement and the corresponding coverage factor. The calculation of the measurement effective degrees of freedom, v_{ef} (med), was performed using the Welch-Satterhwaite equation, Equation (2).

$$v_{ef}(y) = \frac{u_c(y)^4}{\left[\sum_i^N \frac{(u(x_i) \cdot C(x_i))^4}{v_i}\right]}, \tag{2}$$

In Equation (2), N is the number of input variables; v_{ef} is the number of degrees of freedom for each input variable; $u_c(y)$ is the combined standard uncertainty of the output variable; $u(x_i)$ is the standard uncertainty of each input variable; $C(x_i)$ is the sensitivity coefficient of the measurand with respect to each input variable y_i and v_i is the correspondent degrees of freedom.

Finally, the calculation of the contribution of each input variable to the final uncertainty was performed using Equation (3). This analysis is important for identifying potential sources of errors that could compromise the quality of measurement results.

$$Cont(\bar{x}) = \frac{u^2(\bar{x}) \cdot 100\,\%}{u_c^2(D)},$$

(3)

2.2 Implementation of the proposed methodology in MATLAB® R2019a

The proposed methodology was implemented in Excel and MATLAB® R2019a. The code was developed following the calculation steps defined by the GUM method. Therefore, initially, it was defined, as a default, to use the clearvars and clc functions, native to the MATLAB® R2019a language. This practice was adopted with the objective of cleaning the software's cache memory, in addition to possible residues present in the command window, in order to avoid the occurrence of errors due to the substitution of variable values.

Then, the data were incorporated into the calculation scripts with the aid of the readmatrix() function. This function creates vectors by reading data files oriented in columns and separated into structure arrays, a structure that groups related data into compartments called fields. This practice was adopted to facilitate their treatment during calculations.

Subsequently, initial descriptive statistical analyzes were implemented with the mean(), std() and length() functions, which determine, respectively, the mean, standard deviation and sample size, with the objective of identifying the probability distribution of the data. Despite the sample size having been previously defined, the use of the length() function makes it possible for the code to be used in other analyses, so that it is not necessary to change any parameter in the script, but rather that it is adaptable to any set of data. data to be analyzed.

In order to guarantee good reliability to the developed code and calculated results, 21 force values were adopted during the yield strength evaluation. As determined by BIPM et al. (2008), for samples with less than 30 values, the t-Student distribution should be used, implemented in the scripts through the tinv() function. In turn, the values of the coverage factors of the expanded uncertainties of the yield strength were adopted as 95 %.

The code validation was performed by comparing the found results and those obtained via Excel by Antunes (2023).

3. RESULTS AND DISCUSSIONS

3.1. Code implemented in MATLAB for the yield strength

Next, the code implemented in MATLAB®R2019a for calculating the uncertainty associated with the yield strength is shown and detailed and, for a better understanding, it was divided into blocks. The first block, shown in Figure 4, is intended for data import, being a file composed of electronic spreadsheets, one containing the test specimen diameter values, information from the calibration certificates, and another with the force values and information of the Instron machine calibration certificate. The readmatrix function is responsible for reading and importing this data into MATLAB®R2019a.

```
clearvars;
clc;

% Data input

% Influence variables related to the specimen
dataSpecimen = readmatrix('SPECIMEN_LE.xlsx', 'Sheet', '2');

% Values for yield force analysis
dataForce = readmatrix('specimen_LE.xlsx', 'Sheet', '1');
```

Figure 4. Block 1 implemented in MATLAB with data import

The second block, Figure 5, presents the separation of data into specific fields of the measurand, each in its appropriate structure, and then a table is generated, using the table function, for a better visualization of the results of the statistical analysis.

Block 3, Figure 6, is intended for the calculation of the uncertainty of all measurands considered in the calculation of the yield strength uncertainty. They are specimen diameter, circular area, yield strength and yield strength. For the flow limit, for example, initially, all results were stored in a table, referenced by the variable limEsc.Lib, and then all the equations defined by Antunes (2023) were inserted. These equations were used to calculate the standard uncertainty, the combined standard uncertainty, the effective degrees of freedom, the expanded uncertainty, the contribution of the input variables and, finally, the measurement result is presented by the fprintf function. In a similar way, the calculation for the circular area, the maximum force and the yield point was implemented.

```
% Uncertainty associated with the specimen diameter

% Data
diam.readings = dataSpecimen(1,1);
diam.resolution = dataSpecimen(1,2);
diam.covf_calibration = dataSpecimenCP(1,3);
diam.u_ext.calibration = dataSpecimen(1,4);
diam.u_ext.paralelism = dataSpecimen(1,5);
diam.covf_ext = dataSpecimen(1,6);

diam_stat = table(mean(diam.readings), std(diam.readings), length(diam.readings),
'VariableNames', ["Mean", "StandardDeviation", "SampleSize"]);
```

Figure 5. Block 2 implemented in MATLAB for data separation and visualization.

```
% Uncertainty associated with the Yield Strength
yieldS.mean = mean(forceLE.readings)/area.mean;
fprintf('Mean yield strength: %.4f MPa \n', limEsc.cov);

yieldS.inc_pd.comb = sqrt(((-mean(forceLE.readings)/
area.mean^2)^2*diam.inc_pd.comb^2)+((1/
area.mean)^2*(forceLE.inc_pd.var)^2));
fprintf('Standard-uncertainty associated with the yield strength: %.4f MPa\n\n',
limEsc.inc_pd.comb);

% Expanded uncertainty
yieldS.inc_comb.prob = forceLE.inc_comb.prob; % Coverage probability
yields.lib = limEsc.inc_pd.comb^4/((((-mean(forceLE.readings)/
area.mean^2)*diam.inc_pd.comb)^4/(length(diam.readings)-1))+(((1/
area.mean)*forceLE.inc_pd.var)^4/(length(forceLE.readings)-1))); %
Effective degrees of freedom
yieldS.cov = tinv(1 - (1 - limEsc.inc_comb.prob)/2, limEsc.lib); %
Coverage factor
limEsc_Graus = table(yieldS.lib, yieldS.covf, 'VariableNames',
["EffectiveDegreesFreedom", "CoverageFactor"]);
disp(yieldS_Graus);

% Uncertainty contribution
yieldS.cont.area = (((-mean(forceLE.readings)/
area.mean^2)*diam.inc_pd.comb)^2*100)/limEsc.inc_pd.comb^2;
yieldS.cont.forceLE = (((1/area.mean)*forceLE.inc_pd.var)^2*100)/
yieldS.inc_pd.comb^2;
yieldS ContTab = table(yieldS.cont.area,
yieldS.cont.forceLE, 'VariableNames', ["ContArea", "ContForceLE"]);
disp(yieldSContTab);
yieldS.inc_exp = yieldS.cov* yieldS.inc_pd.comb;
fprintf('Expanded uncertainty: %.4f MPa\n\n', yieldS.inc_exp);

% Measurement result
fprintf('RM = %.4f \x00B1 %.4f MPa\n\n', yieldS.mean,
yieldS.inc_exp);
```

Figure 6. Block 3 implemented in MATLAB to determine the uncertainty associated with the yield strength.

3.2. Results of calculating the uncertainty associated with the yield strength for a specimen

The Table 4 summarizes the data used during the calculation of the uncertainty associated with the diameter of the tensile test specimen and the main results. The resulting mean and standard deviation of three diameter measurements were 6.02 mm and 0.27 mm, respectively, for a 68.27 % confidence level.

Table 4. Summary with data used to the calculation of the measurement uncertainty associated with the diameter of the tensile test specimen.

IV	Estimated (mm)	AT	PD	DF	SC	u (mm)	Contribution (%)
$\bar{D}$	6.0200	A	T	2	1	0.0153	63,6
ΔR	0.01	B	R	∞	1	0.0029	2.3
ΔC	0.02	B	N	∞	1	0.0100	27.3
ΔIme	0.01	B	N	∞	1	0.0050	6.8
Combined standard uncertainty $u_c(D)$, mm						0.0191	
Effective degrees of freedom $v_{ef}(D)$						5	
Coverage factor k(D)						2.57	
Expanded uncertainty U(D), mm						0.0492	

In Table 4, IV represents the input variables, AT is the standard uncertainty assessment type, PD is the probability distribution associated with each input variable, DF is the number of degrees of freedom, SC the sensitivity coefficient (derived partial) and *u* is the standard uncertainty associated with each input variable considered.

From Table 4 it can be concluded that the diameter value resulting from the measurement is 6.02 ± 0.05 mm for 95 % coverage probability and a coverage factor k(D) = 2.57. In addition, it is concluded that the input variable that most contributed to the final uncertainty in the diameter measurement was the variability of the readings, representing 63.6 % of the final uncertainty. It is noteworthy that this expanded uncertainty value represents less than 1.0 % of the average diameter value and, therefore, can be considered adequate.

Table 5 shows the results of calculating the uncertainty associated with the cross-sectional area (A) of the tensile test specimen. From Table 5 it can be concluded that the area value is 28.46 ± 0.36 mm^2 for 95 % coverage probability and a coverage factor k(A) = 1.96.

Table 5. Summary with data referring to the calculation of the measurement uncertainty associated with the cross-sectional area of the tensile test specimen.

IV	Estimated (mm^2)	AT	PD	DF	SC	u (mm^2)	Contribution (%)
A	28.4631	A	T	2	89.4196 mm^2	0.01914	100
Combined standard uncertainty $u_c(A)$, mm^2						0.1806	
Effective degrees of freedom $v_{ef}(A)$						∞	
Coverage factor k(A)						1.96	
Expanded uncertainty U(A), mm^2						0.3540	

The applied force corresponding to yield strength values during the test and used in the uncertainty calculation are presented in Table 6. Table 7 shows the summary of the results resulting from the calculation of the uncertainty associated with the yield strength. The yield strength measurement result is 21688.76 ± 103.19 N with 95 % coverage probability and a coverage factor of k(Fe) = 1.97. It is concluded by Tab. 7 that the calibration of the load cell used was the factor that most contributed to the final uncertainty in the force measurement, being responsible for 73.7 % of the uncertainty. This represents 0.5 % of the mean value and can be considered adequate.

Table 6. Force yield strength values (Fe) generated by the universal testing machine during the traction test of the specimen.

Strength (N)			Mean (N)	s (N)
21552.93	21537.48	21556.29		
21562.83	21537.76	21575.29		
21547.88	21544.01	21619.28		
21666.21	21778.55	21814.94	21688.7619	122.6089
21708.26	21799.94	21816.99		
21738.25	21807.62	21816.44		
21819.73	21819.73	21819.73		

Table 7. Summary with data referring to the calculation of the measurement uncertainty associated with the yield strength.

IV	Estimated (N)	AT	PD	DF	SC	u (N)	Contribution (%)
$\bar{F}_e$	21688.7619	A	t	20	1	26.7555	26.0
ΔR	10.00	B	R	∞	1	2.8868	0.3
ΔC	90.00	B	N	∞	1	45.0000	73.7
Combined standard uncertainty $u_c(F_e)$, mm						52.4327	
Effective measurement degrees of freedom $v_{ef}(F_e)$						295	
Measurement coverage factor $k(F_e)$						1.97	
Expanded uncertainty $U(F_e)$, N						103.1910	

Table 8 presents the summary of the results resulting from the calculation of the uncertainty associated with the yield point. The yield strength for the specimen considered is 770.47 ± 2.25 MPa with 95 % coverage probability and a coverage factor of $k(\sigma_y) = 2.10$. It is observed by Tab. 8 that the portion associated with the uncertainty of the force of yield strength was the factor that most contributed to the final uncertainty of the yield strength, accounting for 77.1 % of the uncertainty. This represents 0.3 % of the mean value of the yield point and can be considered adequate.

Table 8. Summary with data referring to the calculation of the measurement uncertainty associated with the yield strength.

IV	Estimated	AT	PD	DF	SC	u	Contribution (%)
A	28.4631 mm²	A	t	1	26.7714 (N/mm⁴)	0.0191 mm²	22.9
Fe	216888.76 N	B	t	20	0.0351 (1/mm²)	26.7575 N	77.1
Combined standard uncertainty $u_c(\sigma_y)$, MPa						1.0706	
Effective degrees of freedom $v_{ef}(\sigma_y)$						18	
Coverage factor $k(\sigma_y)$						2.10	
Expanded uncertainty $U(\sigma_y)$, MPa						2.2482	

3.3. Results of the evaluation of the uncertainty associated with the yield strength considering three specimens

For the assessment of the uncertainty associated with the variability of the yield strength values, three specimens tested under repeatability conditions were analyzed. The uncertainty associated with the yield strength considering the variability of readings for AISI 4340 steel is 10.29 MPa for 95 % coverage probability and a coverage factor $k(\sigma_y) = 4.3$. The expanded uncertainty represents 1.3 % of the mean yield strength value (776.99 MPa) and therefore can be considered adequate. It can be concluded that the yield strength values have adequate repeatability and quality. It is concluded that the uncertainty associated with the variability of the readings does not significantly influence the yield strength results.

Combining the standard uncertainty associated with the variability of the yield strength values for the three test specimens and that resulting from the determination of the yield strength for a specimen, the total uncertainty of the yield strength was obtained. The yield strength value resulting from the tensile test of the AISI 4340 steel for the three specimens is 776.99 ± 4.90 MPa for 95 % coverage probability and a coverage factor $k(\sigma_y) = 2,00$. The expanded uncertainty represents 0.6 % of the average yield strength value, therefore, it can be considered adequate.

Comparing with the literature, it is observed that the expanded uncertainty associated with the yield strength obtained in the experimental conditions of this study is smaller than that obtained by Silva (2004). This author evaluated the uncertainty associated with the yield strength for the steel structural degree RQ 3. Tensile tests were performed by using a Universal Machine Instron model 5500R. The expanded uncertainty associated with the yield strength was of 13 MPa for a mean value of 404 MPa, representing 3.2 %. The uncertainty value obtained by Silva (2004) is adequate, its numerical superiority can be justified because in the summary table presented a "divisor" equal to one was used for three of the six input variables considered. In this column, the number of degrees of freedom associated with each variable should be presented, which in the worst case should be equal to two. It is expected that at least three measurements will be carried out for each measurand considered.

3.4. Validation of the code developed in MATLAB®R2019a

Table 9 shows the values of the combined standard uncertainty, expanded uncertainty and coverage factor obtained via MATLAB®R2019a. This table also presents the values found by Antunes (2023) using Microsoft Excel.

Table 9. Results obtained by the calculation scripts for the evaluation of the uncertainty associated with the yield strength, in comparison with those found by Antunes (2023).

Parameter	MATLAB®R2019a	Antunes (2023)	Difference
Combined standard uncertainty [MPa]	1.0707	1.0706	0.01 %
Expanded uncertainty [MPa]	2.2507	2.2482	0.11 %
Coverage factor	2.1021	2.1000	0.10 %

From Table 9, it is concluded that the code developed in MATLAB®R2019a allowed to determine the combined standard uncertainty and expanded uncertainty values associated with the yield strength in an adequate way. The differences observed in relation to the values obtained by Antunes (2023) are less than or equal to 0.11 %, in both cases. These differences can be attributed to rounding errors. It is worth noting that considering the number of significant digits of the yield strength values these differences are equal to zero.

4. CONCLUSIONS

This work assessed the uncertainty associated with the yield strength obtained through tensile tests using the GUM method. To achieve this, a methodology was developed and implemented using Microsoft Excel® 2019 and MATLAB®R2019a. From the obtained results, the following conclusions can be drawn:

The expanded uncertainty associated with the yield strength obtained through tensile tests for a single specimen, made of AISI 4340 steel (28 HRC), was 2.25 MPa for 95 % coverage probability. This represents 0.3 % of the average (770.47 MPa), indicating that the methodology and instrumentation used in the experimental conditions of this work are suitable.

The yield strength value resulting from the tensile test of the AISI 4340 steel (28 HRC) for the three specimens is 776.99 ± 4.90 MPa for 95 % coverage probability and a coverage factor $k(\sigma_y) = 2{,}00$. The expanded uncertainty represents 0.6 % of the average yield strength value, thus it can be considered appropriate.

The proposed methodology for calculating the measurement uncertainty associated with yield strength was implemented using MATLAB® software and successfully validated. The code developed in MATLAB®R2019a allowed to determine the uncertainty associated with the yield strength in an adequate way. This code facilitates the wider adoption of uncertainty calculations for this important mechanical property and can serve as a foundation (with necessary adjustments) for assessing uncertainty in other measured parameters.

5. ACKNOWLEDGEMENTS

6. REFERENCES

Antunes, J.S. 2023, *Assessment of uncertainty associated with fracture toughness obtained via J-integral*. Dissertation, Universidade Federal de Uberlândia, Uberlândia.

ASTM E8/E8M, 2022, *Standard Test Methods for Tension Testing of Metallic Materials1*. ASTM International, West Conshohocken.

ASTM E8, 1998, *Standard Test Methods for Tension Testing of Metallic*. ASTM International, West Conshohocken.

ASTM E111, 1997, *Standard Test Method for Young's Modulus, Tangent Modulus, and Chord Modulus*. ASTM International, West Conshohocken, 1997.

BIPM, IEC, IFCC, ILAC, ISO, IUPAC, IUPAP and OIML. 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". JCGM 101. 90p.

Graba, Marcin, 2021, *Evaluation of measurement uncertainty in a static tensile test*. Open Engineering, vol. 11, no. 1, pp. 709-722. https://doi.org/10.1515/eng-2021-0069

EN 10002-Part 1, 1990, "Tensile testing - Method of testing at ambient temperature".

EN 10002-Part 5,1990, "Tensile testing - Method of testing at elevated temperature".

Gabauer. W. 2000, *The Determination of Uncertainties in Tensile Testing*. Manual of Codes of Practice for the Determination of Uncertainties in Mechanical Tests on Metallic Materials. Code of Practice No. 07. Austria. 35p.

Silva. L.R.O., 2004, *Evaluation of the uncertainty of measurement of mechanical properties on the tensile testing*. Simposio de Metrología 2004 25 al 27 de Octubre. Mexico.

Xu, T., Wang, K., Song, S., 2021, *Measurement Uncertainty and Representation of Tensile Mechanical Properties in Metals*. Metals, 11, 1733. https://doi.org/10.3390/met11111733

7. RESPONSIBILITY NOTICE

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