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A METROLOGICAL CONTRIBUTION TO THE MEASUREMENT OF LATERAL EXPANSION IN CHARPY TESTS

Rodrigo Freitas Alvarenga
Guilherme Henrique Alves Andrade
João Pedro Cândido José
Luciano José Arantes
Rosenda Valdés Arencibia

Federal University of Uberlândia, 2121, João Naves de Ávila Avenue, Campus Santa Mônica, Building 5F, Zip Code: 38400-902, Uberlândia, MG, Brazil. E-mail addresses: rodrigo.freitas@ltad.com.br, eng.mec.guilhermeandrade@gmail.com, joao.pcandido@hotmail.com, ljarantes@ufu.br, rosenda.arencibia@ufu.br

Daniel Correia Freire Ferreira

Research and Development Center, Petrobras, Rio de Janeiro, Brazil.
E-mail address: danielcff@petrobras.com.br

Abstract. This paper proposes a measurement system based on an analog dial indicator for the lateral expansion measurement. This measurement system was used to measure the expansion of nine reference test specimens ($10 \times 10 \times 55 \text{ mm}^3$) provided by the National Institute of Standards and Technology (NIST) at three energy levels (low, high, and super-high). For each condition, three test specimens were tested using a Charpy 450HIT from Zwick Roell impact machine (8 mm radius striker). Additionally, the effect of the measurement method factor was investigated based on a single factor design. The measurement method factor was investigated on two levels (-1) ASTM method and (1) alternative method (AM), probing opposite points in the test specimen. The Mann-Whitney U test showed that the measurement method factor caused statistically significant effects on the lateral expansion values for five of the nine considered test specimens. The proposed measurement system proved to be simple and feasible. It allows for the acquisition of lateral expansion values with excellent quality. For the worst condition, test specimen 2 at the low energy level (S12), an expanded uncertainty value less than 5.0 % was observed considering the three measurements performed.

Keywords: lateral expansion, charpy impact test, ASTM E23, measurement uncertainty

1. INTRODUCTION

The measure of the ability of the material to resist fracture when subjected to triaxial stresses, such as those at the root of the notch in a Charpy specimen, is the amount of expansion that occurs at this location. The expansion in this case is contraction. Due to the difficulties of measuring this expansion, even after fracture, the expansion that occurs on the opposite end to the flat fracture is usually measured and used as a substitute for contraction (ISO 148-1, 2016). This expansion is called lateral expansion.

According to ASTM E23 (ASTM, 2023), lateral expansion is the maximum increase in the thickness of the specimen as a result of the impact test, expressed in mm. Lateral expansion is an important output parameter in Charpy tests, along with the energy absorbed during impact and the shear fracture appearance. It is worth noting that measuring lateral expansion is not an easy task due to the need to touch half of the fractured specimen on only one side during measurement. It is important to note that according to ASTM E23 (ASTM, 2023), the lateral expansion measurement methods should consider the fact that the fracture path seldom bisects the point of maximum expansion on both sides of a specimen. One half of a broken specimen may include the maximum expansion for both sides, one side only, or neither. Therefore, the expansion on each side of each specimen half should be measured relative to the plane defined by the undeformed portion on the side of the specimen, as shown in Figure 1. In Figure 1, B represents the original thickness of the specimen.

The expansion on each side of each specimen half should be measured relative to the plane defined by the undeformed portion on the specimen side. In this way, A1 and A3 and A2 and A4 are measured. The larger of the two values measured on each half is the specimen's expansion, Eq. (1).

$$EL = \text{Max}(A1 \text{ e } A2) + \text{Max}(A3 \text{ e } A4), \quad (1)$$

ASTM E23 (ASTM, 2023) presents the technical drawing and details of the measurement system based on an analog dial indicator for measuring lateral expansion. By analyzing the technique and the measurement method proposed by this standard, it can be concluded that the greatest difficulty is in manufacturing a device to fix the dial indicator in such a

way that the spindle is perpendicular to the reference surface and consequently to the lateral face of the specimen being measured. ASTM E23 (ASTM, 2023) does not define the number of measurements that should be carry out, nor does it provide guidance on evaluating the uncertainty associated with lateral expansion. It should be noted that all measurements are subject to errors and that when a single measurement is made, for example, there is no possibility of identifying and eliminating gross errors.

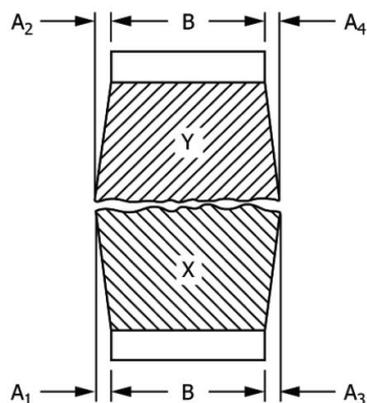


Figure 1. Halves of broken Charpy V-notch impact specimen illustrating the dimensions A1, A2, A3 and A4 which must be measured to calculate the lateral expansion (ASTM E-23, 2023).

In the literature studied, it was observed that different systems and measurement methods are used to measure lateral expansion. Lateral expansion in test specimens made of ABNT 1016 steel was measured with a micrometer (MOURA; VILELA, 2007). Nineteen specimens were machined in the L-T and T-L directions with V notches. Tests were performed at different temperatures. The authors did not specify the type of micrometer used, nor its resolution. The number of measurements performed was also not stated.

The impact properties of three steels, used by NIST to produce Charpy reference test specimens (4340 quenched and tempered with two energy levels and maraging T200 18Ni steel), were investigated through instrumented Charpy tests (LUCON; MCCOWAN; SANTOYO, 2015). For each of the steels, tests were conducted on standardized, sub-size (with 3/4, 1/2, and 1/4 dimensions), and miniaturized test specimens. For each investigated condition, complete transition curves and corresponding transition temperatures were established for the absorbed energy, lateral expansion, and shear fracture appearance. The lateral expansion of the standardized and sub-size specimens was measured with a measurement system like the one recommended by ASTM E-23 (ASTM, 2023). In the miniaturized specimens, lateral expansion was measured with a caliper.

The impact response of specimens sintered from Ti6Al4V powder using an instrumented Charpy testing machine and V-notched specimens was investigated by (MUIRURI et al., 2018). The authors measured lateral expansion using a digital caliper. The authors did not specify the type of caliper used.

Three X70 plates with similar chemical composition and three different thicknesses (13.5 mm; 15.5 mm, and 22.0 mm) were used by (MITCHELL et al., 2021) to manufacture V-notched Charpy specimens. The notches were machined normal to the plate surface in three orientations, 0°, 45°, and 90°, in relation to the rolling direction. In the study, the authors considered 10 temperatures for all conditions. The authors did not specify the measurement system used to measure lateral expansion, nor the procedure used.

The traceability of lateral expansion results is essential for Charpy testing, since this is one of the three output parameters of the Charpy test, used to determine the transition temperature of metallic materials. In this context, obtaining valid and traceable lateral expansion values is of the utmost importance. In accordance with the standard ISO/IEC 17027 (2017), the traceability of measurement results also includes the measurement uncertainty assessment and reporting. According to Désenfant and Priel (2017), the declaration of measurement uncertainty is as important as it is to report the measurement result itself. A measurement or test result without an assessment of its reliability is completely useless. The comparison between different measurements of the same measurand, as well as between a measurement result and a specification limit, are impossible to assess without knowing the uncertainty, JCGM 100 (BIPM, et al (2008).

This paper proposes a measurement system composed of an analog dial indicator, a measurement table, and a device for measuring the expansion on the faces of both parts of a broken specimen. In addition, a methodology based on JCGM 100 (BIPM et al., 2008) is presented to determine the uncertainty associated with lateral expansion. The differences found between the measurement results of lateral expansion using the proposed measurement system and two different measurement methods were also determined. In order to investigate the effect of the measurement method factor on the lateral expansion values, a single factor design was proposed. A statistical analysis was carried out by applying the Mann-Whitney U test using the software STATISTICA®. This analysis aimed to identify if the lateral expansion values were influenced by the measurement method.

2. METHODOLOGY

Tests were conducted on nine standard specimens supplied by NIST using a Zwick Roell Charpy 450HIT impact machine (8 mm radius striker). Table 1 shows the information of the specimens used.

Table 1. Data of the reference specimens tested and reference absorbed energy values.

Code SRM (Standard Reference Material)	Lot	Energy level	Reference absorbed energy values (J)	Expanded uncertainty associated with the certificate value (J)
2093	LL-175	Low	14.9	0.1
2097	HH-178	High	94.8	0.5
2098	SH-58	Super-high	222.3	1.2

Before testing, all specimens were identified as S1, S2, and S3 for each energy level 1-low, 2-high, and 3-super-high considered. The lateral faces of each specimen were also identified as required by ASTM E23 (ASTM, 2023) as A1, A2, A3, and A4. The low and high energy specimens were tested at a temperature of -40 ± 1 °C, while for the super-high energy level specimens the test temperature was 21 ± 1 °C.

The lateral expansion of the nine tested reference specimens ($10 \times 10 \times 55$ mm³), three for each condition, was measured using an analog dial indicator attached to a measurement table, Figure 2. The analog dial indicator has a resolution of 0.001 mm and a nominal range of 2 mm. The calibration certificate declares a systematic error of 4.7 µm for the upper limit of the nominal range and a hysteresis of 1.1 µm. The expanded uncertainty associated with the analog dial indicator calibration is 0.002 mm. During measurement, the specimen was fixed in a device developed for this purpose. Figure 3a shows a 3D image of the device in SolidWorks 2018. The expansion on each face was measured three times.

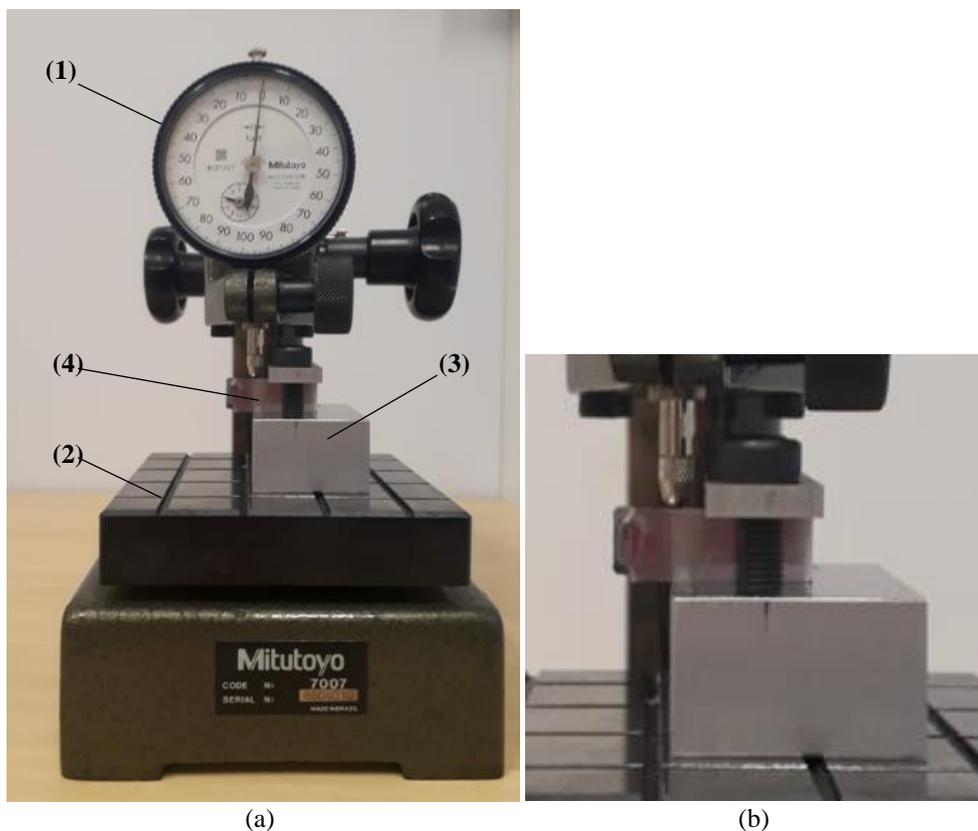


Figure 2. (a) Measurement system used to measure the lateral expansion of Charpy impact test specimens. (1) analog dial indicator, (2) measurement table, and (3) device. (b) Detail with half of the specimen (4) fixed in the measurement device (3).

The device for fixing the specimens was made of AISI 420 steel. The surfaces of the device that support the specimens were initially manufactured by using a computer numerical control (CNC) wire electric discharging machine. They were then ground using a peripheral surface grinding process using a semi-automatic grinding machine, with a z-axis resolution of 5 μm , from the manufacturer MELLO S.A.

The flatness deviation of the upper and lower surfaces of the device and the deviation of parallelism between them were measured using a moving bridge coordinate measuring machine (CMM), manufactured by Mitutoyo, model BR-M442. This CMM has a resolution of 0.5 μm , a work volume of 400 mm (X axis) 400 mm (Y axis) and 300 mm (Z axis). According to the calibration certificate, this CMM has a linear expanded measurement uncertainty of $0.8+L/1500$ mm with a coverage factor k of 2.03 for the X axis; of $0.8+L/3000$ mm with a coverage factor k of 2.08 for the Y axis; and of $0.9+L/2900$ mm with a coverage factor k of 2.11 for the Z axis. The probing error is (1.9 ± 1.2) μm (k = 2.00). The coverage probability is 95 %. A TP20 probe and a MH20i sensor were used during the tests. The measurement in this machine was managed through the Geopak Win software.

The workpiece was placed on the CMM table to conduct the measurements, Fig. 3b. A single tip with a 2 mm diameter ruby sphere was used for probing the points. During the measurement, 21 points were touched on each considered surface. Three measuring cycles were performed. The deviation of flatness of the upper faces was 1.6 ± 0.2 μm and 1.7 ± 0.2 μm , respectively. Meanwhile, the deviation of parallelism assumed 16.7 ± 0.4 μm . In all cases, the coverage probability is 68.27 %.

All measurements were conducted at 20.0 ± 1.0 $^{\circ}\text{C}$. A digital thermo-hygrometer with a nominal range of -20.0 to 60.0 $^{\circ}\text{C}$ and a resolution of 0.1 $^{\circ}\text{C}$ was used to monitor the room temperature. Before conducting the measurements, the measurement system, specimens, and measuring devices remained in the measurement room for 12 h to reach thermal equilibrium.

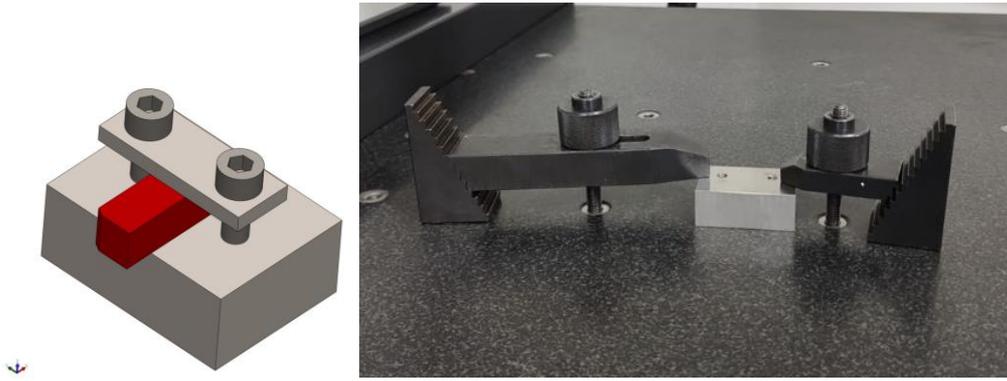


Figure 3. (a) 3D drawing of the measurement device. (b) Base of the device supported on the CMM table during the measurement of flatness and parallelism deviations.

2.1. Measurement uncertainty assessment associated with lateral expansion

The uncertainty associated with lateral expansion was calculated using the GUM method proposed in (BIPM et al., 2008). For this, the mathematical model given in Eq. (1) was used. To facilitate understanding, the maximum value between A1 and A2 was denoted by A and the maximum value between A3 and A4 was denoted by B. Making the necessary substitutions, (2) was obtained.

$$LE = A + B, \quad (2)$$

Applying the law of uncertainty propagation in (2) and calculating the partial derivatives, (3) was obtained. This equation allows calculating the combined standard uncertainty associated with lateral expansion.

$$u_c^2(LE) = \left(\frac{\partial LE}{\partial A}\right)^2 \cdot u^2(A) + \left(\frac{\partial LE}{\partial B}\right)^2 \cdot u^2(B) = u^2(A) + u^2(B) \quad (3)$$

To calculate the standard uncertainty associated with input variables A and B, the following influence factors are considered: variability associated with the average lateral expansion value (\overline{LE}); dial indicator resolution (R); uncertainty associated with the dial indicator calibration (C); and dial indicator hysteresis (H). By making the proper substitutions in (3) the (4) was obtained. This equation allows calculating the combined standard uncertainty associated with lateral expansion.

$$u_c^2(LE) = u^2(\overline{LE}) + 2 \cdot u^2(\Delta R) + 2 \cdot u^2(\Delta C) + 2 \cdot (\Delta H) \quad (4)$$

Table 2 shows the main information about the assessment of the standard uncertainty associated with all input variables.

Table 2. Main information about the assessment of the standard uncertainty associated with all input variables.

Input variable	Type of evaluation	Probability distribution	Degrees of freedom	Equation
\overline{LE}	A	t-Student	2	$u(\overline{LE}) = \frac{s(LE)}{\sqrt{n}}$
R	B	Rectangular	∞	$u(R) = \frac{R}{\sqrt{3}}$
C	B	Normal	∞	$u(C) = \frac{U(C)}{k(C)}$
H	B	Rectangular	∞	$u(H) = \frac{H}{\sqrt{3}}$

In Table 2, $s(\overline{LE})$ is the standard deviation associated with the average lateral expansion value, n is the number of measurement cycles performed, $U(C)$ is the expanded uncertainty associated with the calibration of the dial indicator and $k(C)$ is the corresponding coverage factor.

In order to quantify the effect of the measurement method on lateral expansion values, a single factor design was put forward. The measurement method factor was investigated on two levels: (-1) ASTM E23 method and (+1) alternative method (AM). In the latter, the lateral expansion was adopted as the value of the largest sum shown in (5).

$$EL(AM) = \text{Max}((A1 + A3) \text{ or } (A2 + A4)), \quad (5)$$

This practice was adopted because there are no calipers with a 0.001 mm resolution, and it was not possible to measure the lateral expansion with a micrometer. These two measurement systems touch the specimen at opposite points during the measurement. However, it is unlikely that the largest expansion on both sides of a broken specimen half will be at opposite points. Therefore, the measurement with a micrometer becomes difficult and, in some cases, impracticable. Micrometers have a ratchet that aims to apply a constant force during the measurement and ensure proper contact between the measuring surfaces of the micrometer and the part. For this, three full turns should be applied to the ratchet. When this task is performed, the positioning between micrometer and part is altered and, in some cases, contact is lost.

The statistical analysis of the results was performed using the STATISTICA® software. The Mann-Whitney U test was applied twice. Initially, it was used to test whether the lateral expansion values obtained by both measurement methods, for each energy level, are statistically different or not. Secondly, it was tested whether the lateral expansion values obtained by both measurement methods, for each specimen, are statistically different or not.

3. RESULTS AND DISCUSSION

Tables 3 to 5 show the expansion values found in each phase of the evaluated test specimens for the three considered energy levels and for the three measurement cycles performed. The expanded uncertainty (U) values for 95 % coverage probability are also shown, as well as the average lateral expansion values for each test specimen and for each considered energy level. The largest expansion values obtained in each half of the specimen are highlighted in red.

Table 3. Lateral expansion values (LE) of the low energy test specimens.

	Reading	A1 (mm)	A2 (mm)	A3 (mm)	A4 (mm)	LE (mm)	U(LE) (mm)	Average (mm)	Overall average (mm)
S11	1	0.189	0.000	0.000	0.109	0.298	0.006	0.300	0.215
	2	0.190	0.000	0.000	0.110	0.300			
	3	0.192	0.000	0.000	0.110	0.302			
S21	1	0.074	0.053	0.020	0.036	0.110	0.006	0.111	
	2	0.076	0.055	0.021	0.037	0.113			
	3	0.076	0.054	0.019	0.035	0.111			
S31	1	0.020	0.138	0.097	0.000	0.235	0.006	0.235	
	2	0.021	0.138	0.097	0.000	0.235			
	3	0.018	0.136	0.098	0.000	0.234			

Table 4. Lateral expansion values (LE) of the high energy test specimens.

	Reading	A1 (mm)	A2 (mm)	A3 (mm)	A4 (mm)	LE (mm)	U(LE) mm	Average (mm)	Overall average (mm)
S12	1	0.523	0.195	0.582	0.174	1.105	0.006	1.107	1.083
	2	0.525	0.193	0.582	0.173	1.107			
	3	0.523	0.195	0.585	0.174	1.108			
S22	1	0.185	0.528	0.182	0.565	1.093	0.006	1.091	
	2	0.187	0.525	0.180	0.563	1.088			
	3	0.185	0.529	0.182	0.562	1.091			
S32	1	0.525	0.154	0.526	0.256	1.051	0.006	1.053	
	2	0.528	0.154	0.526	0.257	1.054			
	3	0.527	0.155	0.527	0.255	1.054			

Table 5. Lateral expansion values (LE) of the super-high energy test specimens.

	Reading	A1 (mm)	A2 (mm)	A3 (mm)	A4 (mm)	LE (mm)	U(LE) (mm)	Average (mm)	Overall average (mm)
S13	1	1.362	1.381	1.308	1.170	2.689	0.007	2.685	2.564
	2	1.360	1.380	1.303	1.172	2.683			
	3	1.358	1.378	1.305	1.170	2.683			
S23	1	1.168	1.245	1.209	1.143	2.454	0.007	2.445	
	2	1.169	1.243	1.210	1.144	2.453			
	3	1.170	1.246	1.212	1.143	2.458			
S33	1	1.226	1.233	1.315	1.320	2.553	0.006	2.552	
	2	1.224	1.232	1.317	1.321	2.553			
	3	1.223	1.230	1.318	1.320	2.550			

From Tabs. 3 to 5, it was concluded that lateral expansion assumes 0.215 ± 0.020 J; 1.083 ± 0.020 J and 2.564 ± 0.021 J for a 95 % coverage factor, for low, high and super-high energy levels, respectively. The standard deviation associated with the LE value, considering three specimens for each condition, assumed 0.096 mm, 0.028 mm and 0.115 mm for low, high and super-high energy levels, respectively.

The expanded uncertainty associated with lateral expansion represented in the worst condition (S21) 5.0 % of the average value of lateral expansion. The input variable that contributed the most to the final uncertainty was the one associated with the calibration of the dial indicator, with a contribution of 51.8 %, Figure 4. Similar results were observed for all specimens evaluated.

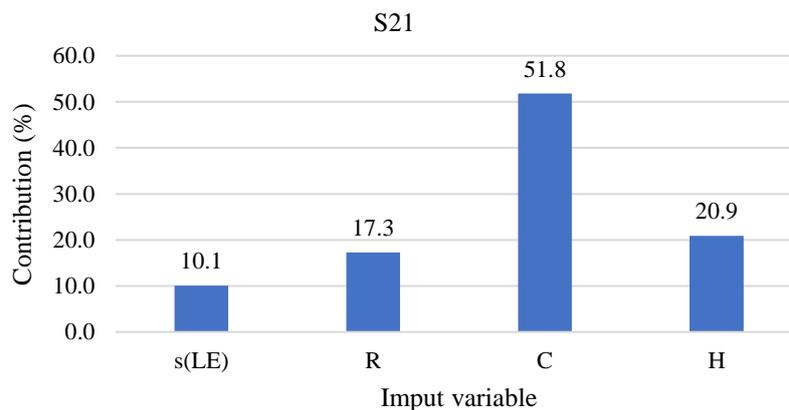


Figure 4. Contribution of input variables to the uncertainty associated with lateral expansion for specimen 2 of the low energy level (S21).

In Tables 3 to 5, it is observed that of the nine specimens evaluated, only four presented the greatest expansion on both sides of a broken half of the specimen.

Figure 5 shows the lateral expansion values obtained for each energy level considered, applying the two measurement methods.

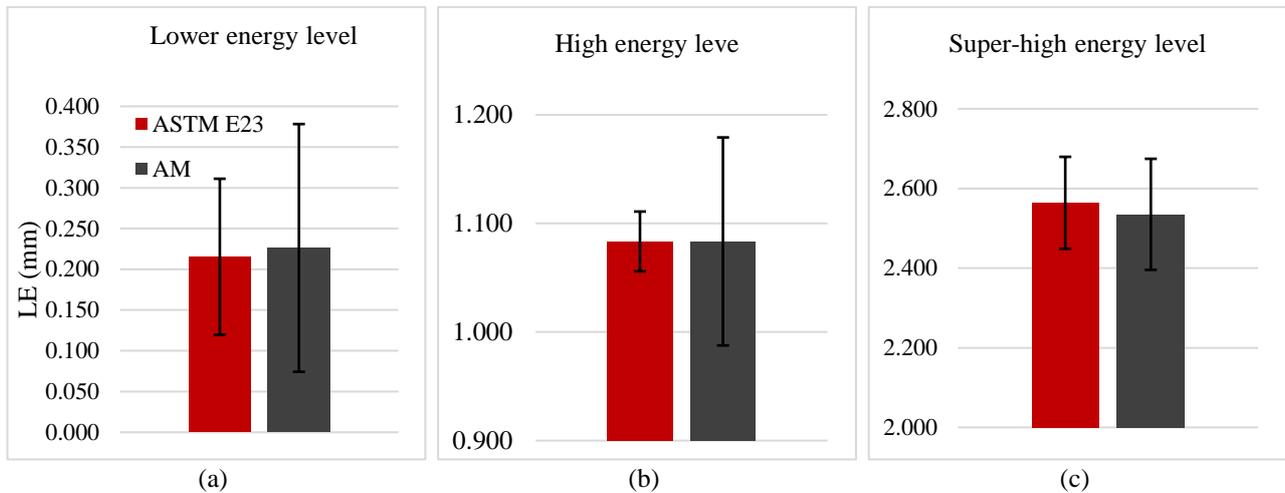


Figure 5. Average lateral expansion values determined according to ASTM E23 (ASTM, 2023) and those obtained by feeling opposite points. The error bars stand for the standard deviation, for a confidence level of 68.27 %.

From Figure 5 it was concluded that the average values of lateral expansion obtained using the two measurement methods are similar. The differences found between the average values were 0.011 mm, 0 and 0.029 mm, respectively for the low, high and super-high energy levels. The error bars that represent the standard deviation, for a confidence level of 68.27 %, are overlaid for the three conditions investigated. In this figure, it is also observed that the lateral expansion values obtained as determined by ASTM E23 (ASTM, 2023) showed better repeatability and consequently lower measurement uncertainty.

The Kolmogorov-Smirnov normality test showed that the LE values follow a normal distribution. p-values > 0.05 (0.17661, 0.24448 and 0.18523) were obtained in all cases. The Mann-Whitney U test was applied using the STATISTICA® software to check if the average lateral expansion values obtained for each condition using the two measurement methods belong to the same population. p-values greater than 0.05 (0.691103, 1.00000 and 0.426777) were obtained in all cases, indicating that there are no statistically significant differences between the average values provided by both methods.

Figure 6 shows the difference (in the same unit of the measurand, mm) observed between the lateral expansion values determined according to ASTM E23 (ASTM, 2023) and those obtained by AM. In turn, Figure 7 shows this difference in percentage.

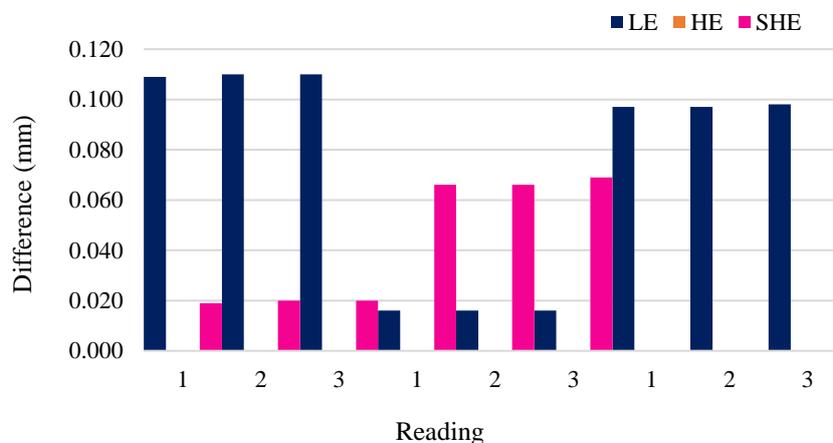


Figure 6. Difference (in mm) observed between the lateral expansion values determined according to ASTM E23 (ASTM, 2023) and those obtained by using the AM.

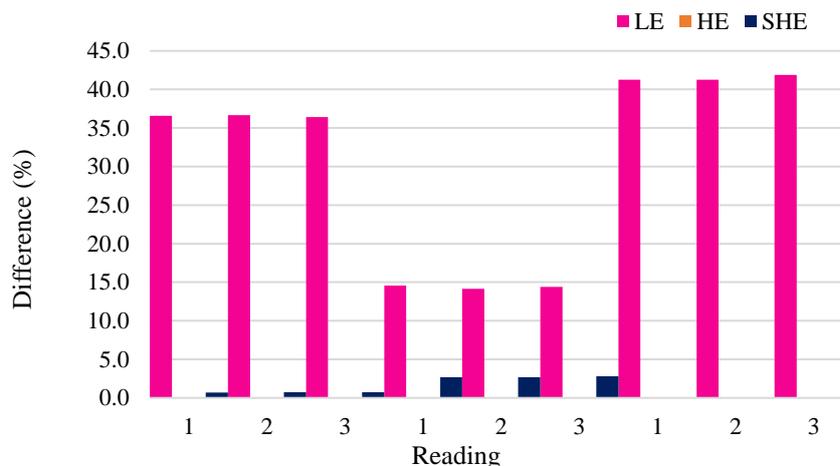


Figure 7. Difference (in percentage) observed between the lateral expansion values determined according to ASTM E23 (ASTM, 2023) and those obtained from applying the AM.

From Figure 6 it is concluded that the greatest differences were observed for the lateral expansion values obtained from low energy specimens. This figure also shows that for these three specimens, this difference is positive, indicating that the values provided by ASTM E23 (ASTM, 2023) are higher than those obtained by the alternative method. For the high energy level, no differences were observed since the greatest expansion was always observed on both sides of one of the broken halves of the specimen. For the super-high energy level, it was observed that for two specimens the lateral expansion values obtained are different. The greatest difference observed was for S23. This assumes 0.069 mm, representing 14.4 % of the lateral expansion value obtained by the ASTM E23 method (ASTM, 2023).

The Mann-Whitney U test was applied again to verify if the average lateral expansion values obtained for each specimen using the two measurement methods belong to the same population. The results obtained are shown in Table 6.

Table 6. Summary of Mann-Whitney U test application for comparing condition specimen for lateral expansion.

	S11	S21	S31	S12	S22	S32	S13	S23	S33
S11	x								
S21		x							
S31			x						
S12				-					
S22					-				
S32						-			
S13							x		
S23								x	
S33									-

From Table 6, the conclusion reached is that with the 95 % confidence level, the factor measurement method caused statistically significant effects on the lateral expansion values for 5 of the 9 specimens considered, p-values less than 0.05 were obtained.

The measurement of expansion on each face of the specimen with an analog dial indicator proved to be subject to reading errors, especially for the super-high energy level where the highest expansion values were observed. It is worth mentioning that, in general, dial indicators with a resolution of 1 μm have a display with 200 μm (one complete turn of the main hand). In this way, the operator must not only read the indication of the main hand, but also count the number of turns that the main hand performs. The possibility of the operator committing reading errors in this case is high. This error can be eliminated using a digital dial indicator.

In the literature studied, it was observed that the caliper (LUCON; MCCOWAN; SANTOYO, 2015; MUIRURI et al., 2018) and the micrometer (MOURA; VILELA, 2007) were used to measure lateral expansion. These measuring systems

can be used as long as the greatest expansion are on both sides of one of the broken halves of the specimen. Otherwise, significant errors can be introduced into the measurement result.

The dial indicator used has a rounded tip which makes the measurement time-consuming, as it is difficult to access the point with the greatest expansion. As determined by ASTM E-23 (ASTM, 2023), a dial indicator with a flat measuring tip should be used.

4. CONCLUSIONS

From the analysis of the results obtained in this work, the following conclusions can be formulated:

- a) The measurement of lateral expansion with a dial indicator and a measurement table proved to be simple and feasible. It is worth noting that this measurement system is in accordance with ASTM E23 determinations (ASTM, 2023).
- b) The measuring device designed and manufactured allowed the broken half of the specimen to be supported and fixed during the measurement satisfactorily.
- c) The result of the measurement of lateral expansion obtained for each specimen exhibited excellent quality with an expanded uncertainty of less than 5.0 %, 0.6 % and 0.3 %, in relation to the average, for the low, high and super high energy level, respectively.
- d) The Mann-Whitney U test showed that the measurement method factor did not cause statistically significant effects on the overall lateral expansion values for the three investigated conditions. However, this test showed that this factor caused statistically significant effects on the lateral expansion values for five of the nine considered test specimens.
- e) The display of the analog dial indicator used (a full turn of the main pointer) is 0.2 mm, which led the pointer to perform up to six turns during the expansion measurement of some specimens. This fact can introduce errors in the reading of the dial indicator. The use of a digital dial indicator is recommended.

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