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Abstract

The Charpy reference specimens produced by NIST for the indirect verification of Charpy machines in accordance with ASTM E23 and ISO 148-1 must satisfy strict dimensional requirements, with tolerances that are in most cases tighter than those prescribed by the standards. In the past, Charpy specimens to be certified were dimensionally inspected by means of an optical comparator (shadowgraph), which has been replaced in 2019 by a digital optical comparator, which provides enhanced measurement accuracy. This report provides step-by-step operating instructions for the dimensional inspection of Charpy certified reference specimens using the digital measurement system, as well as details about its annual recertification, and the NIST dimensional criteria for lot acceptance. Measurements conducted at NIST on five Charpy specimens using the digital comparator were found in excellent agreement with data provided by participants in an ASTM Interlaboratory Study (ILS 1151), demonstrating the accuracy and reliability of the Charpy measurement system currently used at NIST.

Keywords

ASTM E23; Charpy reference specimens; digital optical comparator; dimensional requirements; indirect verification; Interlaboratory Study (ILS); ISO 148-1.

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1. Introduction

The Charpy impact test is a high loading rate test that measures the energy absorbed during fracture, hence providing an indirect measure of impact toughness. For a Charpy machine to maintain an accurate absorbed energy scale, periodic indirect verification[1] with certified reference specimens is required. To achieve the required accuracy, NIST maintains three reference machines (in accordance with ASTM E23 [1]). The average absorbed energy for samples from a given lot tested on these machines is the certified value for the lot.

The NIST Charpy Machine Verification Program in Boulder, Colorado, provides companies and laboratories around the world with an indirect verification service, after taking over in 1989 from the US Army who had started the Program in the late 1960s in Watertown, Massachusetts. Charpy specimen lots of three different energy levels (low, high, and super-high), supplied by qualified vendors, are regularly certified in the NIST Charpy Laboratory. If the certification activities (see below) are successful, the lot (typically consisting of 1,900 Charpy specimens) is shipped to the NIST Office of Reference Materials in Gaithersburg, Maryland, which handles the commercial aspects of the specimen sale.

The certification process for a lot of Charpy indirect verification specimens consists of the following steps:

(a) Random selection of 75 specimens to be tested for certification purposes.
(b) Specimen cleaning from machine oil/dirt.
(c) Dimensional inspection of 30 specimens selected among the 75 pieces above and comparison with the NIST dimensional requirements (dimensional acceptance).
(d) Measurement of Rockwell B hardness on the same 30 specimens mentioned in (c) above.
(e) Impact tests of the 75 specimens selected in (a) above.
(f) Statistical analysis of the results obtained in (e) above (absorbed energy values) to determine the final acceptability of the lot.
(g) In case of acceptable lot, establishment of the certified absorbed energy value and its related uncertainty.

2. Dimensional Specifications for NIST Charpy Reference Specimens

The nominal dimensions for Charpy specimens are prescribed by the reference standards ASTM E23 [1] and ISO 148-1 [2]. The tolerances required by NIST are in most cases stricter than those indicated by both standards, and are summarized in Table 1, along with the nominal values.

Based on the authors' experience, the most influential amongst the dimensions listed in Table 1, which can significantly affect the Charpy test results, are the notch root radius and the ligament.

[1] The machine verification conducted by testing reference specimens is labelled by both ASTM E23 [1] and ISO 148-2 [4] as "indirect", in contrast to the "direct" verification, which consists of the physical inspection of various parts of the machine (foundation, framework, pendulum hammer, anvils, supports, indicating equipment for absorbed energy).

Table 1 - Charpy specimen dimensions and tolerances according to the NIST specifications, ASTM E23, and ISO 148-1. The tightest tolerances are indicated in **bold**.

Dimension	Unit	Nominal value	NIST tolerance	ASTM E23 tolerance	ISO 148-1 tolerance
Length	mm	55	**+0.00 -0.30**	+0.00 -2.50	±0.60
Width	mm	10	**±0.03**	±0.075	±0.075
Thickness	mm	10	**±0.03**	±0.075	±0.11
Squareness of adjacent sides	°	90	**±0.15**	±0.17	±2
Centering of notch	mm	27.5	**±0.20**	±1	±0.42[2]
Ligament length	mm	8	±0.025	±0.025	±0.075
Perpendicularity between notch and specimen longitudinal axis	°	90	**±0.15**	±2	±2
Notch angle	°	45	±1	±1	±2
Notch root radius	mm	0.25	±0.025	±0.025	±0.025

3. Dimensional inspection of Charpy indirect verification specimens

For 30 years (from 1989 until 2019), the dimensional inspection of Charpy specimens was performed by means of a shadowgraph (optical comparator), shown in Figure 1.

Figure 1 – Shadowgraph/optical comparator, used in the past for Charpy specimen dimensional inspection.

[2] For machines with automatic positioning of the specimen, ISO 148-1 recommends the tolerance to be taken as ±0.165 mm.

In 2019, we purchased the digital optical comparator shown in Figure 2.

Figure 2 - Digital optical comparator, currently used for Charpy specimen dimensional inspection.

This report describes the use of this digital comparator within the certification activities of the Charpy Machine Verification program.

3.1. Instructions for the dimensional inspection of Charpy specimens

After the digital comparator was put in service, two programs/macros were developed to measure most of the dimensions listed in Table 1 on groups of Charpy specimens. Each of the relevant programs performs automatic measurements of selected dimensions on groups of 10 Charpy specimens, and is therefore used three times for every specimen lot being certified.

Before performing any dimensional measurements, the specimens must be thoroughly cleaned to remove any oil and dust, particularly from the notch.

After starting the digital comparator, the following login credentials must be entered:

- User: IM-user
- Password: IM-user

The programs used during the certification process are:

(a) 10 Charpy – Side view HP.ssfx: measures length, width, centering of notch, ligament length, notch angle, and notch radius.
(b) 10 Charpy – Top view HP.ssfx: measures thickness.

The specific program is launched from the main menu by clicking “Run”, then “Program”, and selecting it from the list of available programs.

Before placing the 10 Charpy specimens on the glass pane in a 5 row × 2 column pattern (Figure 3), each notch must be accurately cleaned using a hard brush, compressed air, and if necessary, a razor blade to remove any debris that might affect the measurements.

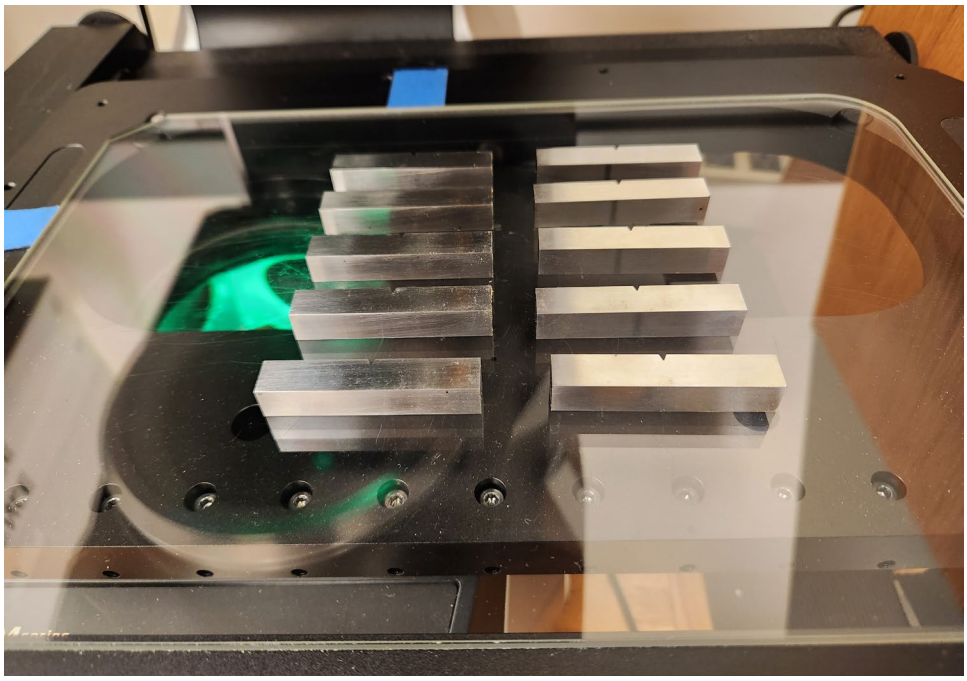


Figure 3 - Ten Charpy specimens placed on the comparator glass surface for dimensional inspection using the program "*10 Charpy - Side view HP*".

Before starting the measurement process, enter the lot identification under "*Lot number*" (for example, "LL-191 pilot"). Measurements are initiated by clicking "Measure", and may take several minutes. Namely, the "*Side view*" program takes much longer than the "*Top view*" program, due to the much higher number of dimensions being measured.

When inspecting specimens with the "*Side View*" program, they need to rest on one of the lateral surfaces with respect to the notch, see Figure 3. When using the "*Top View*" program to measure specimen thickness, the specimens must be turned by 90°, so that the notches face down and the back surfaces face up.

Once measurements are completed, the results are displayed on the screen (Figure 4 shows an example for the "*Side View*" program). Any specimen for which one or more dimensions fall outside the acceptable range according to Table 1 (nominal value ± NIST tolerance), is displayed on the left side of the screen in red with the letters "NG" (not good). Conversely, if the specimen fully complies with NIST requirements, it appears in green with the letters "OK". Should the program fail to identify the expected pattern corresponding to a specimen, the wording "FAIL" will appear.[3] On the right side of the screen, the total number of compliant (OK), non-compliant (NG), and failed (FAIL) specimens is displayed.

[3] In this case, accurately clean the specimen(s) once again, and repeat the measurement.

Figure 4 - Results of the dimensional measurements of 10 Charpy specimens, as displayed on the comparator monitor. Four of the measured specimens do not comply with the NIST requirements (NG).

If one or more specimens are deemed non-compliant with the NIST dimensional specifications after the program is run for the first time, the corresponding samples and notches must be accurately cleaned again. Use the hard brush, compressed air, and also a razor blade to make sure the notch is free from dirt or grime. If the second measurement run still yields non-compliant specimens, the results should be retained.

After completing the measurements, click "Save Report" in the bottom right corner of the screen (Figure 4) to save the results. The available report formats are XPS (default)[4] and CSV (Comma Separated Value). The latter is easily imported into Microsoft Excel[5], and should be used to save Charpy measurement results. Specifically:

(a) Click "Save Report";

(b) From the "Save as type:" drop-down menu, select "CSV (comma separated values)(*.csv);

(c) Enter the file name in the following format: "XX-YYY ZZZ Lot WWW Side view"[6], where:
- XX-YYY is the lot id (e.g., LL-191);
- ZZZ is either "Pilot" or "Production"; and
- WWW is the NIST machine id (SI3, TO2, or TK).

(d) Click "Save".

[4] An XPS document uses a fixed document format, which represents a digital document using the XML mark-up language. XPS stands for "XML Paper Specification". It's similar to the PDF format, but far less popular and with certain limitations.
[5] Certain commercial software, equipment, instruments or materials are identified in this paper to adequately specify the experimental procedure. Such identification is not intended to imply recommendation or endorsement by the National Institute of Standards and Technology, nor is it intended to imply that the equipment or materials identified are necessarily the best available for the purpose.
[6] If the file contains just thickness measurements, use "Top view" instead of "Side view". Make sure the words "Side" or "Top" have an upper case initial ("S" and "T"), while the word "view" is all lower-case.

After completing the measurements, the results must be transferred from the digital comparator to a different computer for further processing, by means of a flash drive.

Click “To Main Menu” in the upper right-hand corner (yellow circle in Figure 4). Select “Optional Settings” at the bottom, then “Import/Export”. An application similar to Windows Explorer will open, see Figure 5. Insert a flash drive into the front of the comparator computer.

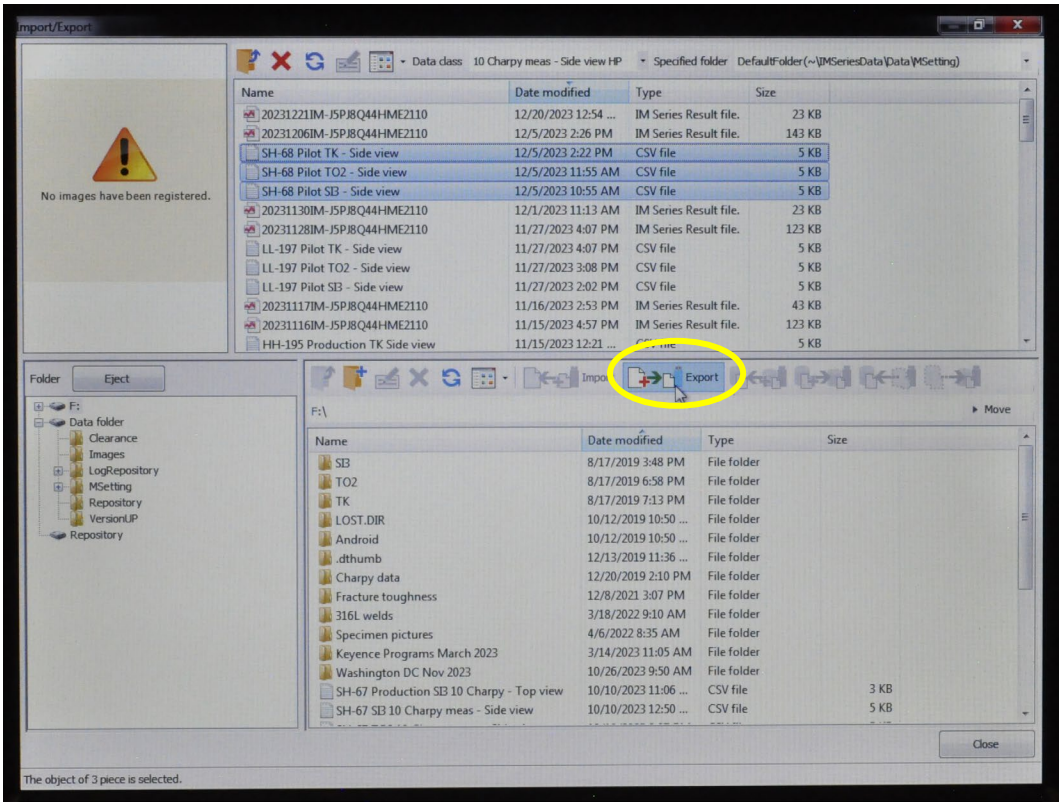


Figure 5 - Screenshot of the "Import/Export" application, used for transferring reports to a flash drive.

To transfer the measurement report(s) obtained from the “Side View” program:

(a) select “10 Charpy – Side view HP” from the “Data class” drop-down menu at the top of the screen;

(b) from the file list in the upper half of the screen, select the files corresponding to the three machines (*e.g.*, “LL-191 Pilot Lot SI3 Side view”, “LL-191 Pilot Lot TO2 Side view”, “LL-191 Pilot Lot TK Side view”);

(c) In the lower left-hand part of the screen, select drive “F:” (corresponding to the flash drive); its contents will be displayed in the lower half of the screen;

(d) Click “Export” in the middle of the screen (yellow circle in Figure 5), and verify the files now appear in the bottom half.

After selecting “10 Charpy – Top View HP” from the “Data class” drop-down menu, repeat steps (b)-(d) above to transfer the three files containing the thickness measurements to the flash drive.

Once the transfer of the six measurement files (three generated by the "Side view" and three by the "Top view" program) to a flash drive is accomplished, the digital comparator can be shut down (click "Close" twice in the bottom right-hand corner, then click the Power button).

3.2. Preparation of the Charpy lot dimensional report

Before the measurements can be imported into Microsoft Excel[7], the six CSV files must be copied from the flash drive into the "Charpy data" folder of the Charpy secondary computer. It is imperative that the file names correspond exactly to the following format (using the example above):

- *LL-191 Pilot Lot SI3 Side view.csv*
- *LL-191 Pilot Lot TO2 Side view.csv*
- *LL-191 Pilot Lot TK Side view.csv*
- *LL-191 Pilot Lot SI3 Top view.csv*
- *LL-191 Pilot Lot TO2 Top view.csv*
- *LL-191 Pilot Lot TK Top view.csv*

Once the files are copied in the "Charpy data" folder, they must be individually renamed as follows:

- *SI3 Side view.csv*
- *TO2 Side view.csv*
- *TK Side view.csv*
- *SI3 Top view.csv*
- *TO2 Top view.csv*
- *TK Top view.csv*

Open the macro-enabled spreadsheet "*Charpy lot dimensional measurement template.xlsm*". The spreadsheet contains three sheets, labeled "SI3 machine", "TO2 machine", and "TK machine". The first sheet ("SI3 machine") features two buttons, called "CLEAR ALL MEASUREMENTS" and "IMPORT KEYENCE MEASUREMENTS".[7]

Clicking "CLEAR ALL MEASUREMENTS" will delete all existing measurements on all three sheets, so that new measurements can be imported from the CSV files that have been renamed in the previous step. Specifically, the contents of the fields "Measured value", "Corrected value", "Acceptable? (YES/NO)", and "Notes"[8] will be erased. The headers of each sheet ("Measurement date:" and "Lot id:") will also be cleared.

New measurements are imported by clicking "IMPORT KEYENCE MEASUREMENTS",[7] **as long as the six files listed above exist in the directory and their names are exactly as indicated (including upper/lower cases)**. Once the import process is completed without error messages, the information for each measured specimen will look as shown in Figure 6.

[7] Certain commercial software, equipment, instruments, or materials are identified in this paper to adequately specify the experimental procedure. Such identification is not intended to imply recommendation or endorsement by the National Institute of Standards and Technology, nor is it intended to imply that the equipment or materials identified are necessarily the best available for the purpose.
[8] Except for the last four rows for each specimen ("Ang adj sides…").

The dimensions measured by means of the digital optical comparator are shown in the column "Measured value". The following column ("Corrected value") displays the measurement after applying the correction resulting from the latest annual recertification (see Section 4 for details). Note that corrected measurements are automatically rounded to the nearest 0.01 mm, as this is considered to be a reasonable level of accuracy for the measurements.

Specimen 2

Dimension	Unit	Measured value	Corrected value	Nominal value	NIST tolerances Min	NIST tolerances Max	Acceptable? (YES/NO)	NOTES
Length [L]	mm	54.868	54.87	55	54.7	55	YES	
Notch centering	mm	0.028	0.03	0	-0.2	0.2	YES	
Width [W]	mm	9.989	9.99	10	9.97	10.03	YES	
Thickness [B]	mm	9.999	10.00	10	9.97	10.03	YES	
Ligament [b]	mm	8.004	8.00	8	7.975	8.025	YES	
Notch radius [ρ]	mm	0.255	0.26	0.25	0.225	0.275	YES	
Notch angle [α]	°	44.49	44.49	45	44	46	YES	
Angle adj sides 1	°			90	89.85	90.15		(*)
Angle adj sides 2	°			90	89.85	90.15		(*)
Angle adj sides 3	°			90	89.85	90.15		(*)
Angle adj sides 4	°			90	89.85	90.15		(*)

Perpendicularity measurements (mm)

Next specimen

Figure 6 - Measurements for a single Charpy specimen after importing data from the comparator's CSV files.

The corrected measurements are checked for validity with respect to the nominal values in the next column and the NIST tolerances (shown in terms of minimum and maximum acceptable values). If the corrected measurement is acceptable, "YES" is displayed on a green background. Otherwise (Figure 7):

- if the corrected measurement is within $X_{nom} \pm 2x_{tol}$ (where X_{nom} is the nominal value and x_{tol} is the NIST tolerance), "NO" is displayed on a pink background;
- if the corrected measurement is within $X_{nom} \pm 2x_{tol}$, "NO" is displayed on a pink background and "**OUTSIDE ±2·TOL**" is printed in bold red font in the "NOTES" column.

Specimen 5

Dimension	Unit	Measured value	Corrected value	Nominal value	NIST tolerances Min	NIST tolerances Max	Acceptable? (YES/NO)	NOTES
Length [L]	mm	54.837	54.83	55	54.7	55	YES	
Notch centering	mm	0.013	0.01	0	-0.2	0.2	YES	
Width [W]	mm	9.965	9.96	10	9.97	10.03	NO	
Thickness [B]	mm	10.108	10.10	10	9.97	10.03	NO	OUTSIDE ±2·TOL
Ligament [b]	mm	8.014	8.01	8	7.975	8.025	YES	
Notch radius [ρ]	mm	0.255	0.255	0.25	0.225	0.275	YES	
Notch angle [α]	°	44.01	44.01	45	44	46	YES	
Angle adj sides 1	°			90	89.85	90.15		(*)
Angle adj sides 2	°			90	89.85	90.15		(*)
Angle adj sides 3	°			90	89.85	90.15		(*)
Angle adj sides 4	°			90	89.85	90.15		(*)

Figure 7 - Examples of non-compliant corrected measurements: width (within $X_{nom} \pm 2x_{tol}$) and thickness (outside $X_{nom} \pm 2x_{tol}$).

For each measured specimen, the last four rows contain the measurements related to the squareness/perpendicularity of adjacent sides, expressed in degrees (acceptable values are 90 ° ± 0.15°). Specimen squareness is verified by means of a special gauge/micrometer, shown in Figure 8. Measurements are taken on the four sides of each specimen, and transferred to the

secondary Charpy computer by pressing the "Data" button on the connector of an SPC (Statistical Process Control) cable that is plugged into one of the USB ports of the computer. Data transfer happens into one of the four cells under the heading "Perpendicularity measurements (mm)" in column L (Figure 6). Pressing "Data" on the connector prints the linear value l_i (with i = 1 to 4) in the selected cell, and moves the cursor to the cell underneath. Clicking the link "Next specimen" moves the cursor to the first cell of the next specimen on the sheet.

The corresponding angle α_i is automatically calculated as:

$$\alpha_i = 90° - arcsin\left(\frac{l_i}{10}\right) \quad (1)$$

and displayed in columns C & D (merged).

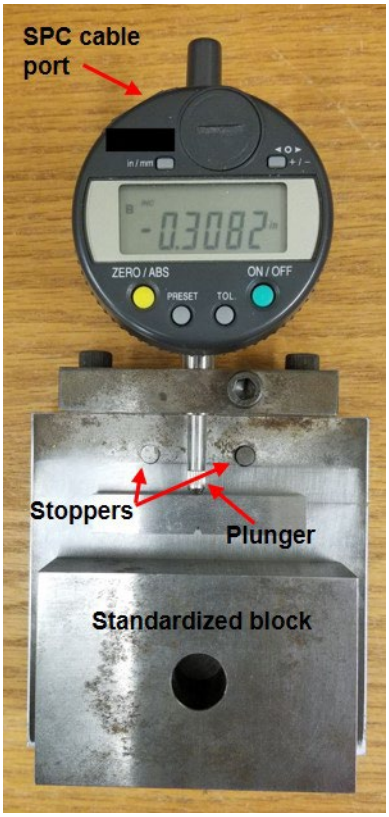


Figure 8 – Gage/micrometer used to verify the squareness of Charpy verification specimens.

An example of Charpy Lot Dimensional Measurement Report is presented in Appendix A.

4. Annual recertification of the digital optical comparator

The annual recertification of the digital comparator consists of the following steps.

(a) Measurement of the two artifacts pictured in Figure 9: a ring with nominal inner diameter 20.32 mm ± 0.0084 mm and a plug with diameter 2.54 mm ± 0.005 mm.

(b) Measurement of 12 certified gage blocks with nominal dimensions 0.5 mm, 1 mm, 1.5 mm, 2 mm, 3 mm, 5 mm, 7.5 mm, 10 mm, 20 mm, 40 mm, 60 mm, and 80 mm.

(c) Measurement of certified angle blocks (Figure 10) corresponding to nominal values of 15°, 30°, and 45°.

(d) Measurement of certified radius gage (Figure 11) corresponding to 0.010” (0.254 mm).

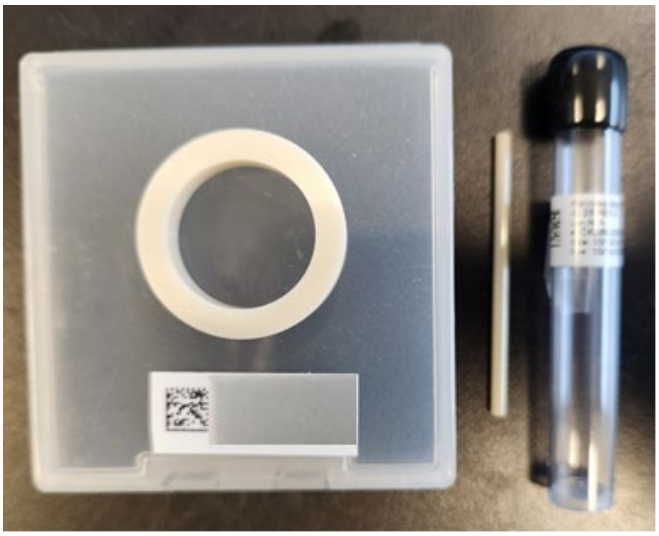


Figure 9 - Artifacts used for the recertification of the digital optical comparator: ring (left) and plug (right).

Step (a), using two artifacts, is executed by means of a program called “*Recertification Program (plug + ring).lsfx*”. If the measurements (inner diameter of the ring and diameter of the plug) are within the nominal values ± the specified tolerances, the instrument is in good working condition. Each measurement is performed in two different modes: high-accuracy and wide-field. The Recertification Program Report for 2023 is presented in Appendix B.

Step (b), using gage blocks, verifies the linear measurements and determines the corrections to be used for the dimensional controls of Charpy verification specimens. Twelve different blocks, with dimensions ranging from 0.5 mm to 80 mm, are measured, repeating each measurement five times. The average bias between measurements and nominal dimension is calculated for each block and provided in the Recertification Report.

The correction of the measured Charpy dimensions in the spreadsheet “*Charpy lot dimensional measurement template.xlsm*” is performed as follows:

- If the Charpy dimension corresponds to one of the gage blocks (*e.g.*, thickness and width = 10 mm), the average bias obtained from the recertification is subtracted from the measured dimension.
- If the Charpy dimension does not correspond to one of the gage blocks (*e.g.*, length = 55 mm), the correction is established by linearly interpolating between the deviations corresponding to the blocks immediately below and above (*e.g.*, 40 mm and 60 mm block).

Step (c) verifies angle measurements. Although the only angle directly measured by the digital comparator is the notch angle (nominal value = 45°), the following angles are verified (5 replicates per angle): 15°, 30°, and 45°. The first two are directly measured on the corresponding blocks, while the third is measured by juxtaposing the 15° and 30° blocks. The average deviation calculated for the 45° block is used to correct the measured Charpy notch angles.

Figure 10 - Set of certified angle blocks between 1° and 30°.

Step (d) verifies the notch root radius of the Charpy specimens (0.25 mm ± 0.025 mm according to both NIST and ASTM E23 specifications). The concave radius indicated by the red circle in Figure 11 corresponds to 0.01 in., or 0.0254 mm. The average deviation of 5 repeated measurements will be used to correct notch root radius measurements when certifying Charpy verification lots.

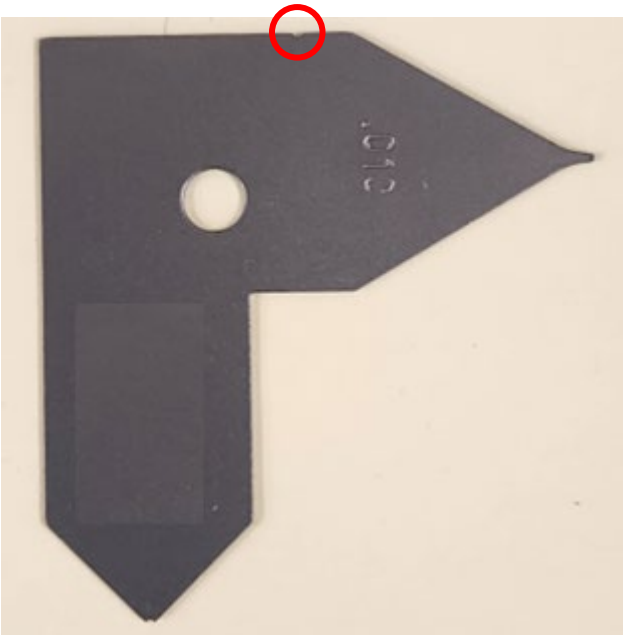


Figure 11 - Certified decimal radius corresponding to 0.010" (0.254 mm).

The 2023 Recertification Report for linear dimensions, angles, and radius is reproduced in Appendix C.

5. NIST dimensional acceptance specifications for Charpy indirect verification specimen lots

Based on the dimensional measurements collected in the Charpy lot dimensional report described in Section 3.2 and the corrections based on the annual recertification of the digital comparator as detailed in Section 4, a pilot or production lot of Charpy indirect verification specimens is considered dimensionally acceptable if all the following requirements are met:

(1) No more than **one** of the 30 inspected specimens (3.3 %) have any dimensions falling outside a range corresponding to the **nominal value ± twice the NIST tolerance**.

(2) No more than **six** of the 30 inspected specimens (20 %) have any dimensions falling outside a range corresponding to the **nominal value ± once the NIST tolerance**.

(3) No more than **three** of the 30 inspected specimens (10 %) have **two or more** dimensions falling outside a range corresponding to the **nominal value ± once the NIST tolerance**.

6. Comparison of NIST 2023 measurements with the results of an ASTM ILS (Interlaboratory Study)

Towards the end of the 2010s, the ASTM E08.07.07 Task Group (responsible for the E23 standard) conducted an Interlaboratory Study (ILS) to evaluate the ability of Charpy testing laboratories to accurately measure the critical specimen dimension by means of various measurement techniques [3]. Five Charpy specimens, fabricated from a low alloy steel using grinding and electrical discharge machining (EDM) to cut the notches, were circulated among 25 participating labs, which included NIST Boulder. The critical dimensions of the notches (ligament, notch root radius, and notch angle) were purposedly varied with respect to the nominal dimensions of the ASTM E23 specification. Each organization was asked to repeat each measurement three times, using their normal methods and personnel. Measurements concerning the notch had to be performed on both sides of the specimen (A and B), as the fabrication process can lead to variations in the notch across the thickness.

Although NIST was one of the participants, the digital optical comparator had not been purchased yet, and the ILS measurements were obtained by means of the old measurement system (Deltronic optical comparator – Figure 1). NIST measurements were performed by three different individuals, including two of the authors of this report.

In 2023, the original specimens used in the ILS were obtained by the coordinator (D. A. Conley from Newport News Shipbuilding), so that measurements could be repeated using the digital optical comparator, and compared with the ILS results reported in [3]. The following specimen dimensions were measured in 2023 by the authors of this report using the digital optical comparator:

- Ligament, b (mm)
- Notch root radius, ρ (mm)
- Notch angle, α (°)
- Width, W (mm)
- Thickness, B (mm).

The first three dimensions listed above were measured twice, once on side A and once on side C (Figure 12); the last two (width and thickness) were measured only once.

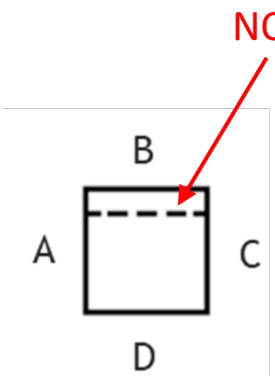


Figure 12 - Cross section of a Charpy specimen.

Table 2 (ligament, notch root radius, and notch angle) and Table 3 (width and thickness) assemble the results obtained at NIST in 2023 and compare them with the mean values and standard deviations from the ILS.

Table 2 – Ligament, notch root radius, and notch angle measurements obtained at NIST in 2023 using the digital optical comparator and comparison with average values and standard deviations from the ASTM ILS.

Specimen number	Specimen side	Ligament b (mm)			Notch radius ρ (mm)			Notch angle α (°)		
		EL	RS	AE	EL	RS	AE	EL	RS	AE
1	A	8.0476	8.0504	8.0446	0.2851	0.2842	0.2784	46.78	46.80	46.88
		ILS: 8.037 mm ± 0.015 mm			*ILS: 0.273 mm ± 0.016 mm*			*ILS: 46.89° ± 0.45°*		
	C	8.0474	8.0445	8.0497	0.2917	0.2776	0.2921	46.83	46.21	46.81
		ILS: 8.041 mm ± 0.013 mm			*ILS: 0.273 mm ± 0.022 mm*			*ILS: 46.97° ± 0.54°*		
2	A	8.0294	8.0280	8.0301	0.2727	0.2697	0.2724	45.64	45.64	45.66
		ILS: 8.024 mm ± 0.009 mm			*ILS: 0.265 mm ± 0.013 mm*			*ILS: 45.60° ± 0.38°*		
	C	8.0304	8.0305	8.0284	0.2716	0.2737	0.2713	45.65	45.68	45.61
		ILS: 8.021 mm ± 0.018 mm			*ILS: 0.261 mm ± 0.017 mm*			*ILS: 45.66° ± 0.39°*		
3	A	7.9777	7.9871	7.9763	0.2283	0.2385	0.2341	45.20	44.84	45.15
		ILS: 7.966 mm ± 0.019 mm			*ILS: 0.226 mm ± 0.026 mm*			*ILS: 45.61° ± 0.62°*		
	C	7.9853	7.9753	7.9853	0.2382	0.2342	0.2368	44.83	45.14	44.92
		ILS: 7.972 mm ± 0.016 mm			*ILS: 0.229 mm ± 0.028 mm*			*ILS: 45.24° ± 0.45°*		
4	A	7.9859	7.9845	7.9839	0.2412	0.2376	0.2371	43.15	43.78	43.84
		ILS: 7.984 mm ± 0.011 mm			*ILS: 0.239 mm ± 0.012 mm*			*ILS: 44.25° ± 0.51°*		
	C	7.9861	7.9830	7.9868	0.2376	0.2364	0.2394	43.86	43.46	43.86
		ILS: 7.984 mm ± 0.012 mm			*ILS: 0.238 mm ± 0.010 mm*			*ILS: 44.23° ± 0.48°*		
5	A	7.9655	7.9753	7.9659	0.2260	0.2288	0.2237	42.90	42.97	42.85
		ILS: 7.962 mm ± 0.018 mm			*ILS: 0.229 mm ± 0.015 mm*			*ILS: 43.20° ± 0.68°*		
	C	7.9735	7.9657	7.9725	0.2129	0.2255	0.2257	42.53	42.79	42.73
		ILS: 7.962 mm ± 0.012 mm			*ILS: 0.227 mm ± 0.015 mm*			*ILS: 43.19° ± 0.61°*		

Legend: EL = Enrico Lucon; RS = Ray Santoyo; AE = Allen Eckhardt.

Table 3 – Width and thickness measurements obtained at NIST in 2023 using the digital optical comparator and comparison with average values and standard deviations from the ASTM ILS (in *italic*).

Specimen number	Width *W* (mm)			Thickness *B* (mm)		
	EL	RS	AE	EL	RS	AE
1	10.010	10.010	10.009	10.036	10.031	10.031
	ILS: 10.005 mm ± 0.008 mm			*ILS: 10.025 mm ± 0.008 mm*		
2	10.007	10.009	10.006	10.019	10.023	10.023
	ILS: 10.006 mm ± 0.007 mm			*ILS: 10.019 mm ± 0.009 mm*		
3	10.009	10.008	10.008	10.014	10.014	10.013
	ILS: 10.007 mm ± 0.006 mm			*ILS: 10.012 mm ± 0.007 mm*		
4	10.006	10.007	10.006	10.016	10.017	10.015
	ILS: 10.006 mm ± 0.011 mm			*ILS: 10.021 mm ± 0.012 mm*		
5	10.019	10.017	10.019	10.038	10.031	10.037
	ILS: 10.005 mm ± 0.006 mm			*ILS: 10.021 mm ± 0.009 mm*		

Note that the comparison between the ILS results and NIST 2023 measurement could have been the subject of a Gage R & R (Repeatability & Reproducibility) Study, which is used to define the amount of variation in the measurement data due to the measurement system. However, such a rigorous and detailed approach is outside the scope of this report, and data are herein compared in purely graphical form, as detailed below. The main objective here is to show that our measurements are consistent with those provided by other laboratories using a variety of techniques and types of equipment.

Graphical comparisons between ASTM ILS results and NIST measurements are shown in Appendix D in the form of probability density functions for the former and data points lying on the bell curves for the latter. For the ILS results provided by participating laboratories, a normal distribution was assumed, and the Gaussian/bell curve was obtained using the mean value of the specimen dimension, μ, and its standard deviation σ according to the equation:

$$f(x) = \frac{1}{\sigma\sqrt{2\pi}} e^{-\frac{1}{2}\left(\frac{x-\mu}{\sigma}\right)^2} \quad , \tag{2}$$

where x is the specimen dimension and $f(x)$ is the probability density function, or frequency.

Examples are shown in Figure 13 (specimen #1, ligament size A) and Figure 14 (specimen #3, notch angle side C).

For a normal distribution, about 68 % of the values are within one standard deviation from the mean, while about 95 % lie within two standard deviations, and about 99.7 % within three standard deviations. In Table 4 and Table 5, we indicate, for every specimen dimension, where each of the NIST 2023 measurements lies with respect to the mean of the corresponding ILS combined results: * (within $\pm 1\sigma$), ** (between $\pm 1\sigma$ and $\pm 2\sigma$), and *** (within $\pm 2\sigma$ and $\pm 3\sigma$). This information is also color-coded: green, yellow, and red, respectively.

The overall distribution of our results with respect to the ASTM ILS data is summarized in Table 6. The best agreement is for the notch root radius (all NIST measurements fall within one standard deviation of the mean), while the worst agreement was observed for the thickness

(73.3 % of the NIST measurements lie within $\mu \pm 1\sigma$) and the width (80 % within $\mu \pm 1\sigma$, but 13.3 % lie between $\mu \pm 2\sigma$ and $\mu \pm 3\sigma$). Considering all the measurements, 89.2 % lie within ± one standard deviation of the ILS mean values. None fall outside $\mu \pm 3\sigma$.

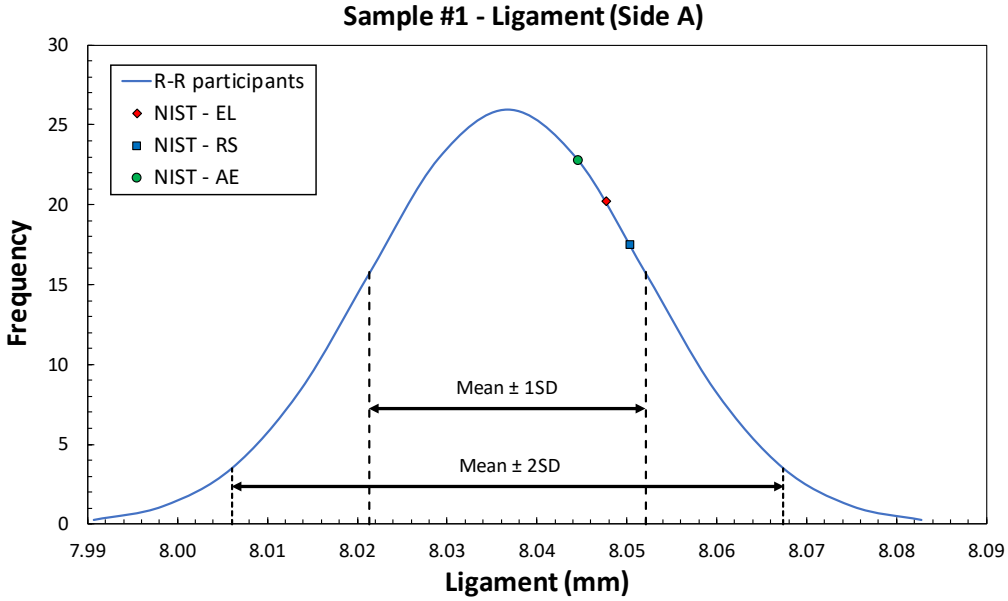


Figure 13 - Comparison between ASTM ILS result distribution and NIST 2023 measurements for the ligament of specimen #1 (side A).

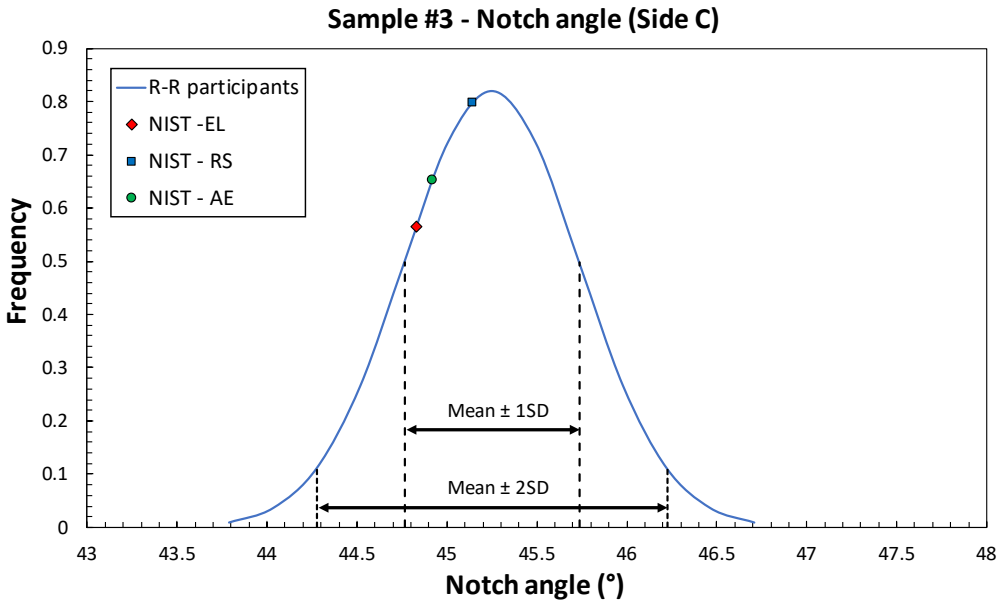


Figure 14 - Comparison between ASTM ILS result distribution and NIST 2023 measurements for the notch angle of specimen #3 (side C).

We therefore conclude that the comparison between the Charpy dimensional measurements performed at NIST by means of the digital optical comparator and the results of the ASTM E28.07 Interlaboratory Study is favorable.

Table 4 - Location of NIST 2023 measurements for ligament, notch root radius, and notch angle.
LEGEND – * = within $\mu \pm 1\sigma$, ** = within $\mu \pm 2\sigma$, *** = within $\mu \pm 3\sigma$.

Charpy dimension	Specimen #	Specimen side	NIST measurements 2023 EL	RS	AE
Ligament	1	A	*	*	*
		C	*	*	*
	2	A	*	*	*
		C	*	*	*
	3	A	*	**	*
		C	*	*	*
	4	A	*	*	*
		C	*	*	*
	5	A	*	*	*
		C	*	*	*
Notch root radius	1	A	*	*	*
		C	*	*	*
	2	A	*	*	*
		C	*	*	*
	3	A	*	*	*
		C	*	*	*
	4	A	*	*	*
		C	*	*	*
	5	A	*	*	*
		C	*	*	*
Notch angle	1	A	*	*	*
		C	*	**	*
	2	A	*	*	*
		C	*	*	*
	3	A	*	**	*
		C	*	*	*
	4	A	***	*	*
		C	*	**	*
	5	A	*	*	*
		C	**	*	*

Table 5 - Location of NIST 2023 measurements for thickness and width.

Charpy dimension	Specimen #	NIST measurements 2023 EL	RS	AE
Thickness	1	**	*	*
	2	*	*	*
	3	*	*	*
	4	*	*	*
	5	**	**	**
Width	1	*	*	*
	2	*	*	*
	3	*	*	*
	4	*	*	*
	5	***	**	***

Table 6 - Overall distribution of the NIST 2023 measurements.

Charpy dimension	Within $\mu \pm 1\sigma$	Within $\mu \pm 2\sigma$	Within $\mu \pm 3\sigma$
Ligament	96.7%	3.3%	0.0%
Notch root radius	100.0%	0.0%	0.0%
Notch angle	83.3%	13.3%	3.3%
Thickness	73.3%	26.7%	0.0%
Width	80.0%	6.7%	13.3%
ALL	**89.2%**	**8.3%**	**2.5%**

7. Conclusions

The use of a digital optical comparator, purchased by NIST in 2019, enables accurate dimensional measurements of Charpy specimens randomly selected from lots of reference samples used for the indirect verification of Charpy machines. Specifically, it allows verifying if the specimen dimensions satisfy the NIST specifications, which are in most cases stricter (*i.e.*, tighter tolerances) than those indicated by both the ASTM E23 and ISO 148-1 standards.

The operating instructions and the procedural steps for the dimensional inspection of Charpy reference specimens using the digital measurement system have been provided in this report, as well as a description of the annual instrument recertification, based on the measurement of various artifacts, in terms of linear dimensions, angles, and radiuses. The NIST dimensional acceptance specifications have been detailed; a lot that fulfils such specifications and exhibits acceptable variability based on the test results (absorbed energy) can be successfully certified.

As a final quality check of the measurements provided by the digital optical comparator, the results of an ASTM Interlaboratory Study (ILS) conducted in the late 2010s have been compared with measurements obtained in 2023 at NIST by three different users on the same five Charpy samples originally used in the ILS. It was found that the vast majority of NIST measurements (89.2 %) fall within the ILS mean value ± one standard deviation, and only 2.5 % differ from the respective ILS mean values by more than twice the standard deviation.

References

[1] ASTM E23-23a, *Standard Test Methods for Notched Impact Testing of Metallic Materials*, ASTM International, West Conshohocken, PA. https://doi.org/10.1520/E0023-23A

[2] ISO 148-1:2016, *Metallic materials — Charpy pendulum impact test — Part 1: Test method*, International Standards Organization, Geneva, Switzerland.

[3] Conley DA and Pline TR (2023) Investigation of Measurement Capability for Charpy V-Notch Specimens Using Typical Measurement Practices. *Journal of Testing and Evaluation* 51(6):4190-4206. https://doi.org/10.1520/JTE20220047

[4] ISO 148-2:2016, *Metallic materials — Charpy pendulum impact test — Part 2: Verification of testing machines*, International Standards Organization, Geneva, Switzerland.

Appendix A. Charpy Lot Dimensional Report

CHARPY LOT DIMENSIONAL MEASUREMENT REPORT

Measurement date: 12/5/2023 **Machine:** SI3
Lot id: SH-68
Measuring instruments: Keyence IM-7030 + Mitutoyo perpendicularity gage (*)

Specimen 1

Dimension	Unit	Measured value	Corrected value	Nominal value	NIST tolerances Min	NIST tolerances Max	Acceptable? (YES/NO)	NOTES
Length [L]	mm	54.867	54.86	55	54.7	55	YES	
Notch centering	mm	0.001	0.00	0	-0.2	0.2	YES	
Width [W]	mm	10.006	10.00	10	9.97	10.03	YES	
Thickness [B]	mm	10.100	10.10	10	9.97	10.03	NO	OUTSIDE ±2·TOL
Ligament [b]	mm	8.018	8.01	8	7.975	8.025	YES	
Notch radius [ρ]	mm	0.251	0.25	0.25	0.225	0.275	YES	
Notch angle [α]	°	44.18	44.18	45	44	46	YES	
Angle adj sides 1	°	89.93		90	89.85	90.15	YES	(*)
Angle adj sides 2	°	89.81		90	89.85	90.15	NO	(*)
Angle adj sides 3	°	89.89		90	89.85	90.15	YES	(*)
Angle adj sides 4	°	89.91		90	89.85	90.15	YES	(*)

Specimen 2

Dimension	Unit	Measured value	Corrected value	Nominal value	NIST tolerances Min	NIST tolerances Max	Acceptable? (YES/NO)	NOTES
Length [L]	mm	54.868	54.87	55	54.7	55	YES	
Notch centering	mm	0.028	0.03	0	-0.2	0.2	YES	
Width [W]	mm	9.989	9.99	10	9.97	10.03	YES	
Thickness [B]	mm	9.999	10.00	10	9.97	10.03	YES	
Ligament [b]	mm	8.004	8.00	8	7.975	8.025	YES	
Notch radius [ρ]	mm	0.255	0.26	0.25	0.225	0.275	YES	
Notch angle [α]	°	44.49	44.49	45	44	46	YES	
Angle adj sides 1	°	89.99		90	89.85	90.15	YES	(*)
Angle adj sides 2	°	90.13		90	89.85	90.15	YES	(*)
Angle adj sides 3	°	89.71		90	89.85	90.15	NO	(*)
Angle adj sides 4	°	90.04		90	89.85	90.15	YES	(*)

Specimen 3

Dimension	Unit	Measured value	Corrected value	Nominal value	NIST tolerances Min	NIST tolerances Max	Acceptable? (YES/NO)	NOTES
Length [L]	mm	54.865	54.862	55	54.7	55	YES	
Notch centering	mm	0.011	0.011	0	-0.2	0.2	YES	
Width [W]	mm	9.993	9.989	10	9.97	10.03	YES	
Thickness [B]	mm	10.006	10.002	10	9.97	10.03	YES	
Ligament [b]	mm	8.019	8.014	8	7.975	8.025	YES	
Notch radius [ρ]	mm	0.254	0.254	0.25	0.225	0.275	YES	
Notch angle [α]	°	44.81	44.81	45	44	46	YES	
Angle adj sides 1	°	89.97		90	89.85	90.15	YES	(*)
Angle adj sides 2	°	90.11		90	89.85	90.15	YES	(*)
Angle adj sides 3	°	90.02		90	89.85	90.15	YES	(*)
Angle adj sides 4	°	90.05		90	89.85	90.15	YES	(*)

Specimen 4

Dimension	Unit	Measured value	Corrected value	Nominal value	NIST tolerances Min	NIST tolerances Max	Acceptable? (YES/NO)	NOTES
Length [L]	mm	54.845	54.84	55	54.7	55	YES	
Notch centering	mm	0.006	0.01	0	-0.2	0.2	YES	
Width [W]	mm	9.984	9.98	10	9.97	10.03	YES	
Thickness [B]	mm	10.002	10.00	10	9.97	10.03	YES	
Ligament [b]	mm	8.016	8.01	8	7.975	8.025	YES	
Notch radius [ρ]	mm	0.256	0.256	0.25	0.225	0.275	YES	
Notch angle [α]	°	43.64	43.64	45	44	46	NO	
Angle adj sides 1	°			90	89.85	90.15		(*)
Angle adj sides 2	°			90	89.85	90.15		(*)
Angle adj sides 3	°			90	89.85	90.15		(*)
Angle adj sides 4	°			90	89.85	90.15		(*)

Specimen 5

Dimension	Unit	Measured value	Corrected value	Nominal value	NIST tolerances Min	NIST tolerances Max	Acceptable? (YES/NO)	NOTES
Length [L]	mm	54.837	54.83	55	54.7	55	YES	
Notch centering	mm	0.013	0.01	0	-0.2	0.2	YES	
Width [W]	mm	9.965	9.96	10	9.97	10.03	NO	
Thickness [B]	mm	10.108	10.10	10	9.97	10.03	NO	OUTSIDE ±2·TOL
Ligament [b]	mm	8.014	8.01	8	7.975	8.025	YES	
Notch radius [ρ]	mm	0.255	0.255	0.25	0.225	0.275	YES	
Notch angle [α]	°	44.01	44.01	45	44	46	YES	
Angle adj sides 1	°	89.99		90	89.85	90.15	YES	(*)
Angle adj sides 2	°	90.03		90	89.85	90.15	YES	(*)
Angle adj sides 3	°	90.03		90	89.85	90.15	YES	(*)
Angle adj sides 4	°	90.02		90	89.85	90.15	YES	(*)

Specimen 6

Dimension	Unit	Measured value	Corrected value	Nominal value	NIST tolerances Min	NIST tolerances Max	Acceptable? (YES/NO)	NOTES
Length [L]	mm	54.859	54.86	55	54.7	55	YES	
Notch centering	mm	0.015	0.02	0	-0.2	0.2	YES	
Width [W]	mm	9.99	9.99	10	9.97	10.03	YES	
Thickness [B]	mm	9.992	9.99	10	9.97	10.03	YES	
Ligament [b]	mm	8.007	8.00	8	7.975	8.025	YES	
Notch radius [ρ]	mm	0.246	0.246	0.25	0.225	0.275	YES	
Notch angle [α]	°	44.29	44.29	45	44	46	YES	
Angle adj sides 1	°	90.03		90	89.85	90.15	YES	(*)
Angle adj sides 2	°	90.03		90	89.85	90.15	YES	(*)
Angle adj sides 3	°	90.28		90	89.85	90.15	NO	(*)
Angle adj sides 4	°	89.80		90	89.85	90.15	NO	(*)

Specimen 7

Dimension	Unit	Measured value	Corrected value	Nominal value	NIST tolerances Min	NIST tolerances Max	Acceptable? (YES/NO)	NOTES
Length [L]	mm	54.87	54.87	55	54.7	55	YES	
Notch centering	mm	0.011	0.01	0	-0.2	0.2	YES	
Width [W]	mm	9.995	9.99	10	9.97	10.03	YES	
Thickness [B]	mm	10.01	10.01	10	9.97	10.03	YES	

Ligament [b]	mm	8.024	8.02	8	7.975	8.025	YES	
Notch radius [ρ]	mm	0.255	0.255	0.25	0.225	0.275	YES	
Notch angle [α]	°	44.3	44.3	45	44	46	YES	
Angle adj sides 1	°	89.99		90	89.85	90.15	YES	(*)
Angle adj sides 2	°	90.14		90	89.85	90.15	YES	(*)
Angle adj sides 3	°	89.98		90	89.85	90.15	YES	(*)
Angle adj sides 4	°	90.09		90	89.85	90.15	YES	(*)

Specimen 8

Dimension	Unit	Measured value	Corrected value	Nominal value	NIST tolerances Min	NIST tolerances Max	Acceptable? (YES/NO)	NOTES
Length [L]	mm	54.839	54.84	55	54.7	55	YES	
Notch centering	mm	0.005	0.01	0	-0.2	0.2	YES	
Width [W]	mm	9.993	9.99	10	9.97	10.03	YES	
Thickness [B]	mm	10.009	10.01	10	9.97	10.03	YES	
Ligament [b]	mm	8.008	8.00	8	7.975	8.025	YES	
Notch radius [ρ]	mm	0.251	0.251	0.25	0.225	0.275	YES	
Notch angle [α]	°	44.31	44.31	45	44	46	YES	
Angle adj sides 1	°	90.04		90	89.85	90.15	YES	(*)
Angle adj sides 2	°	90.01		90	89.85	90.15	YES	(*)
Angle adj sides 3	°	90.13		90	89.85	90.15	YES	(*)
Angle adj sides 4	°	90.04		90	89.85	90.15	YES	(*)

Specimen 9

Dimension	Unit	Measured value	Corrected value	Nominal value	NIST tolerances Min	NIST tolerances Max	Acceptable? (YES/NO)	NOTES
Length [L]	mm	54.851	54.85	55	54.7	55	YES	
Notch centering	mm	0.009	0.01	0	-0.2	0.2	YES	
Width [W]	mm	10.009	10.01	10	9.97	10.03	YES	
Thickness [B]	mm	10.009	10.01	10	9.97	10.03	YES	
Ligament [b]	mm	8.025	8.02	8	7.975	8.025	YES	
Notch radius [ρ]	mm	0.251	0.251	0.25	0.225	0.275	YES	
Notch angle [α]	°	44.11	44.11	45	44	46	YES	
Angle adj sides 1	°	90.04		90	89.85	90.15	YES	(*)
Angle adj sides 2	°	90.06		90	89.85	90.15	YES	(*)
Angle adj sides 3	°	90.02		90	89.85	90.15	YES	(*)
Angle adj sides 4	°	90.07		90	89.85	90.15	YES	(*)

Specimen 10

Dimension	Unit	Measured value	Corrected value	Nominal value	NIST tolerances Min	NIST tolerances Max	Acceptable? (YES/NO)	NOTES
Length [L]	mm	54.856	54.85	55	54.7	55	YES	
Notch centering	mm	0.002	0.00	0	-0.2	0.2	YES	
Width [W]	mm	9.993	9.99	10	9.97	10.03	YES	
Thickness [B]	mm	9.975	9.97	10	9.97	10.03	YES	
Ligament [b]	mm	8.004	8.00	8	7.975	8.025	YES	
Notch radius [ρ]	mm	0.251	0.251	0.25	0.225	0.275	YES	
Notch angle [α]	°	44.53	44.53	45	44	46	YES	
Angle adj sides 1	°	90.11		90	89.85	90.15	YES	(*)
Angle adj sides 2	°	89.89		90	89.85	90.15	YES	(*)
Angle adj sides 3	°	90.05		90	89.85	90.15	YES	(*)
Angle adj sides 4	°	89.98		90	89.85	90.15	YES	(*)

CHARPY LOT DIMENSIONAL MEASUREMENT REPORT

Measurement date: 12/5/2023 **Machine:** TO2
Lot id: SH-68
Measuring instruments: **Keyence IM-7030 + Mitutoyo perpendicularity gage (*)**

Specimen 1

Dimension	Unit	Measured value	Corrected value	Nominal value	NIST tolerances Min	NIST tolerances Max	Acceptable? (YES/NO)	NOTES
Length [L]	mm	54.871	54.87	55	54.7	55	YES	
Notch centering	mm	0	0.00	0	-0.2	0.2	YES	
Width [W]	mm	10.01	10.01	10	9.97	10.03	YES	
Thickness [B]	mm	10.003	10.00	10	9.97	10.03	YES	
Ligament [b]	mm	8.021	8.02	8	7.975	8.025	YES	
Notch radius [ρ]	mm	0.257	0.257	0.25	0.225	0.275	YES	
Notch angle [α]	°	44.39	44.39	45	44	46	YES	
Angle adj sides 1	°	89.98		90	89.85	90.15	YES	(*)
Angle adj sides 2	°	90.11		90	89.85	90.15	YES	(*)
Angle adj sides 3	°	90.00		90	89.85	90.15	YES	(*)
Angle adj sides 4	°	89.98		90	89.85	90.15	YES	(*)

Specimen 2

Dimension	Unit	Measured value	Corrected value	Nominal value	NIST tolerances Min	NIST tolerances Max	Acceptable? (YES/NO)	NOTES
Length [L]	mm	54.865	54.86	55	54.7	55	YES	
Notch centering	mm	0.014	0.01	0	-0.2	0.2	YES	
Width [W]	mm	9.992	9.99	10	9.97	10.03	YES	
Thickness [B]	mm	10.001	10.00	10	9.97	10.03	YES	
Ligament [b]	mm	8.024	8.02	8	7.975	8.025	YES	
Notch radius [ρ]	mm	0.247	0.247	0.25	0.225	0.275	YES	
Notch angle [α]	°	44.29	44.29	45	44	46	YES	
Angle adj sides 1	°	90.05		90	89.85	90.15	YES	(*)
Angle adj sides 2	°	90.06		90	89.85	90.15	YES	(*)
Angle adj sides 3	°	90.03		90	89.85	90.15	YES	(*)
Angle adj sides 4	°	90.05		90	89.85	90.15	YES	(*)

Specimen 3

Dimension	Unit	Measured value	Corrected value	Nominal value	NIST tolerances Min	NIST tolerances Max	Acceptable? (YES/NO)	NOTES
Length [L]	mm	54.861	54.86	55	54.7	55	YES	
Notch centering	mm	0.011	0.01	0	-0.2	0.2	YES	
Width [W]	mm	9.996	9.99	10	9.97	10.03	YES	
Thickness [B]	mm	9.993	9.99	10	9.97	10.03	YES	
Ligament [b]	mm	8.022	8.02	8	7.975	8.025	YES	
Notch radius [ρ]	mm	0.251	0.251	0.25	0.225	0.275	YES	
Notch angle [α]	°	44.32	44.32	45	44	46	YES	
Angle adj sides 1	°	90.07		90	89.85	90.15	YES	(*)
Angle adj sides 2	°	90.25		90	89.85	90.15	NO	(*)
Angle adj sides 3	°	89.83		90	89.85	90.15	NO	(*)
Angle adj sides 4	°	90.05		90	89.85	90.15	YES	(*)

Specimen 4

Dimension	Unit	Measured value	Corrected value	Nominal value	NIST tolerances Min	NIST tolerances Max	Acceptable? (YES/NO)	NOTES
Length [L]	mm	54.856	54.85	55	54.7	55	YES	
Notch centering	mm	0.007	0.01	0	-0.2	0.2	YES	
Width [W]	mm	9.988	9.98	10	9.97	10.03	YES	
Thickness [B]	mm	10.007	10.00	10	9.97	10.03	YES	
Ligament [b]	mm	8.018	8.01	8	7.975	8.025	YES	
Notch radius [ρ]	mm	0.254	0.254	0.25	0.225	0.275	YES	
Notch angle [α]	°	44.26	44.26	45	44	46	YES	
Angle adj sides 1	°	89.91		90	89.85	90.15	YES	(*)
Angle adj sides 2	°	90.10		90	89.85	90.15	YES	(*)
Angle adj sides 3	°	90.03		90	89.85	90.15	YES	(*)
Angle adj sides 4	°	90.17		90	89.85	90.15	NO	(*)

Specimen 5

Dimension	Unit	Measured value	Corrected value	Nominal value	NIST tolerances Min	NIST tolerances Max	Acceptable? (YES/NO)	NOTES
Length [L]	mm	54.862	54.86	55	54.7	55	YES	
Notch centering	mm	0.005	0.01	0	-0.2	0.2	YES	
Width [W]	mm	9.994	9.99	10	9.97	10.03	YES	
Thickness [B]	mm	10.008	10.00	10	9.97	10.03	YES	
Ligament [b]	mm	8.024	8.02	8	7.975	8.025	YES	
Notch radius [ρ]	mm	0.246	0.246	0.25	0.225	0.275	YES	
Notch angle [α]	°	44.42	44.42	45	44	46	YES	
Angle adj sides 1	°	90.05		90	89.85	90.15	YES	(*)
Angle adj sides 2	°	90.06		90	89.85	90.15	YES	(*)
Angle adj sides 3	°	90.02		90	89.85	90.15	YES	(*)
Angle adj sides 4	°	90.03		90	89.85	90.15	YES	(*)

Specimen 6

Dimension	Unit	Measured value	Corrected value	Nominal value	NIST tolerances Min	NIST tolerances Max	Acceptable? (YES/NO)	NOTES
Length [L]	mm	54.862	54.86	55	54.7	55	YES	
Notch centering	mm	0.014	0.01	0	-0.2	0.2	YES	
Width [W]	mm	9.989	9.99	10	9.97	10.03	YES	
Thickness [B]	mm	10.008	10.00	10	9.97	10.03	YES	
Ligament [b]	mm	8.022	8.02	8	7.975	8.025	YES	
Notch radius [ρ]	mm	0.257	0.257	0.25	0.225	0.275	YES	
Notch angle [α]	°	44.15	44.15	45	44	46	YES	
Angle adj sides 1	°	90.05		90	89.85	90.15	YES	(*)
Angle adj sides 2	°	90.01		90	89.85	90.15	YES	(*)
Angle adj sides 3	°	90.02		90	89.85	90.15	YES	(*)
Angle adj sides 4	°	90.05		90	89.85	90.15	YES	(*)

Specimen 7

Dimension	Unit	Measured value	Corrected value	Nominal value	NIST tolerances Min	NIST tolerances Max	Acceptable? (YES/NO)	NOTES
Length [L]	mm	54.841	54.84	55	54.7	55	YES	
Notch centering	mm	0.006	0.01	0	-0.2	0.2	YES	
Width [W]	mm	9.991	9.99	10	9.97	10.03	YES	
Thickness [B]	mm	10.009	10.01	10	9.97	10.03	YES	

Ligament [b]	mm	8.017	8.01	8	7.975	8.025	YES	
Notch radius [ρ]	mm	0.253	0.253	0.25	0.225	0.275	YES	
Notch angle [α]	°	44.5	44.5	45	44	46	YES	
Angle adj sides 1	°	90.11		90	89.85	90.15	YES	(*)
Angle adj sides 2	°	90.07		90	89.85	90.15	YES	(*)
Angle adj sides 3	°	90.03		90	89.85	90.15	YES	(*)
Angle adj sides 4	°	90.05		90	89.85	90.15	YES	(*)

Specimen 8

Dimension	Unit	Measured value	Corrected value	Nominal value	NIST tolerances Min	NIST tolerances Max	Acceptable? (YES/NO)	NOTES
Length [L]	mm	54.839	54.84	55	54.7	55	YES	
Notch centering	mm	0.003	0.00	0	-0.2	0.2	YES	
Width [W]	mm	10.009	10.01	10	9.97	10.03	YES	
Thickness [B]	mm	10.007	10.00	10	9.97	10.03	YES	
Ligament [b]	mm	8.022	8.02	8	7.975	8.025	YES	
Notch radius [ρ]	mm	0.257	0.257	0.25	0.225	0.275	YES	
Notch angle [α]	°	44.17	44.17	45	44	46	YES	
Angle adj sides 1	°	90.00		90	89.85	90.15	YES	(*)
Angle adj sides 2	°	90.03		90	89.85	90.15	YES	(*)
Angle adj sides 3	°	89.99		90	89.85	90.15	YES	(*)
Angle adj sides 4	°	90.02		90	89.85	90.15	YES	(*)

Specimen 9

Dimension	Unit	Measured value	Corrected value	Nominal value	NIST tolerances Min	NIST tolerances Max	Acceptable? (YES/NO)	NOTES
Length [L]	mm	54.833	54.83	55	54.7	55	YES	
Notch centering	mm	0.005	0.01	0	-0.2	0.2	YES	
Width [W]	mm	9.997	9.99	10	9.97	10.03	YES	
Thickness [B]	mm	10.004	10.00	10	9.97	10.03	YES	
Ligament [b]	mm	8.018	8.01	8	7.975	8.025	YES	
Notch radius [ρ]	mm	0.243	0.243	0.25	0.225	0.275	YES	
Notch angle [α]	°	44.49	44.49	45	44	46	YES	
Angle adj sides 1	°	90.33		90	89.85	90.15	NO	(*)
Angle adj sides 2	°	90.10		90	89.85	90.15	YES	(*)
Angle adj sides 3	°	89.93		90	89.85	90.15	YES	(*)
Angle adj sides 4	°	89.78		90	89.85	90.15	NO	(*)

Specimen 10

Dimension	Unit	Measured value	Corrected value	Nominal value	NIST tolerances Min	NIST tolerances Max	Acceptable? (YES/NO)	NOTES
Length [L]	mm	54.853	54.85	55	54.7	55	YES	
Notch centering	mm	0.001	0.00	0	-0.2	0.2	YES	
Width [W]	mm	9.992	9.99	10	9.97	10.03	YES	
Thickness [B]	mm	10.014	10.01	10	9.97	10.03	YES	
Ligament [b]	mm	8.013	8.01	8	7.975	8.025	YES	
Notch radius [ρ]	mm	0.239	0.239	0.25	0.225	0.275	YES	
Notch angle [α]	°	44.52	44.52	45	44	46	YES	
Angle adj sides 1	°	89.79		90	89.85	90.15	NO	(*)
Angle adj sides 2	°	90.33		90	89.85	90.15	NO	(*)
Angle adj sides 3	°	89.74		90	89.85	90.15	NO	(*)
Angle adj sides 4	°	90.26		90	89.85	90.15	NO	(*)

CHARPY LOT DIMENSIONAL MEASUREMENT REPORT

Measurement date: 12/5/2023 **Machine:** TK
Lot id: SH-68
Measuring instruments: **Keyence IM-7030 + Mitutoyo perpendicularity gage (*)**

Specimen 1

Dimension	Unit	Measured value	Corrected value	Nominal value	NIST tolerances Min	NIST tolerances Max	Acceptable? (YES/NO)	NOTES
Length [L]	mm	54.855	54.85	55	54.7	55	YES	
Notch centering	mm	0.017	0.02	0	-0.2	0.2	YES	
Width [W]	mm	9.997	9.99	10	9.97	10.03	YES	
Thickness [B]	mm	10.009	10.01	10	9.97	10.03	YES	
Ligament [b]	mm	8.017	8.01	8	7.975	8.025	YES	
Notch radius [ρ]	mm	0.246	0.246	0.25	0.225	0.275	YES	
Notch angle [α]	°	45.24	45.24	45	44	46	YES	
Angle adj sides 1	°	90.15		90	89.85	90.15	YES	(*)
Angle adj sides 2	°	90.14		90	89.85	90.15	YES	(*)
Angle adj sides 3	°	89.90		90	89.85	90.15	YES	(*)
Angle adj sides 4	°	90.02		90	89.85	90.15	YES	(*)

Specimen 2

Dimension	Unit	Measured value	Corrected value	Nominal value	NIST tolerances Min	NIST tolerances Max	Acceptable? (YES/NO)	NOTES
Length [L]	mm	54.863	54.86	55	54.7	55	YES	
Notch centering	mm	0.012	0.01	0	-0.2	0.2	YES	
Width [W]	mm	9.993	9.99	10	9.97	10.03	YES	
Thickness [B]	mm	10.005	10.00	10	9.97	10.03	YES	
Ligament [b]	mm	8.021	8.02	8	7.975	8.025	YES	
Notch radius [ρ]	mm	0.251	0.251	0.25	0.225	0.275	YES	
Notch angle [α]	°	44.71	44.71	45	44	46	YES	
Angle adj sides 1	°	90.17		90	89.85	90.15	NO	(*)
Angle adj sides 2	°	89.85		90	89.85	90.15	YES	(*)
Angle adj sides 3	°	90.01		90	89.85	90.15	YES	(*)
Angle adj sides 4	°	90.02		90	89.85	90.15	YES	(*)

Specimen 3

Dimension	Unit	Measured value	Corrected value	Nominal value	NIST tolerances Min	NIST tolerances Max	Acceptable? (YES/NO)	NOTES
Length [L]	mm	54.868	54.87	55	54.7	55	YES	
Notch centering	mm	0.015	0.02	0	-0.2	0.2	YES	
Width [W]	mm	9.998	9.99	10	9.97	10.03	YES	
Thickness [B]	mm	10.003	10.00	10	9.97	10.03	YES	
Ligament [b]	mm	8.024	8.02	8	7.975	8.025	YES	
Notch radius [ρ]	mm	0.25	0.25	0.25	0.225	0.275	YES	
Notch angle [α]	°	44.56	44.56	45	44	46	YES	
Angle adj sides 1	°	90.11		90	89.85	90.15	YES	(*)
Angle adj sides 2	°	89.98		90	89.85	90.15	YES	(*)
Angle adj sides 3	°	90.06		90	89.85	90.15	YES	(*)
Angle adj sides 4	°	90.02		90	89.85	90.15	YES	(*)

Specimen 4

Dimension	Unit	Measured value	Corrected value	Nominal value	NIST tolerances Min	NIST tolerances Max	Acceptable? (YES/NO)	NOTES
Length [L]	mm	54.858	54.855	55	54.7	55	YES	
Notch centering	mm	0.013	0.013	0	-0.2	0.2	YES	
Width [W]	mm	9.993	9.989	10	9.97	10.03	YES	
Thickness [B]	mm	10.008	10.004	10	9.97	10.03	YES	
Ligament [b]	mm	8.017	8.012	8	7.975	8.025	YES	
Notch radius [ρ]	mm	0.245	0.245	0.25	0.225	0.275	YES	
Notch angle [α]	°	44.65	44.65	45	44	46	YES	
Angle adj sides 1	°	89.99		90	89.85	90.15	YES	(*)
Angle adj sides 2	°	90.02		90	89.85	90.15	YES	(*)
Angle adj sides 3	°	90.01		90	89.85	90.15	YES	(*)
Angle adj sides 4	°	90.03		90	89.85	90.15	YES	(*)

Specimen 5

Dimension	Unit	Measured value	Corrected value	Nominal value	NIST tolerances Min	NIST tolerances Max	Acceptable? (YES/NO)	NOTES
Length [L]	mm	54.868	54.87	55	54.7	55	YES	
Notch centering	mm	0.005	0.01	0	-0.2	0.2	YES	
Width [W]	mm	9.992	9.99	10	9.97	10.03	YES	
Thickness [B]	mm	10.004	10.00	10	9.97	10.03	YES	
Ligament [b]	mm	8.024	8.02	8	7.975	8.025	YES	
Notch radius [ρ]	mm	0.254	0.254	0.25	0.225	0.275	YES	
Notch angle [α]	°	44.66	44.66	45	44	46	YES	
Angle adj sides 1	°	90.19		90	89.85	90.15	NO	(*)
Angle adj sides 2	°	90.05		90	89.85	90.15	YES	(*)
Angle adj sides 3	°	90.20		90	89.85	90.15	NO	(*)
Angle adj sides 4	°	89.91		90	89.85	90.15	YES	(*)

Specimen 6

Dimension	Unit	Measured value	Corrected value	Nominal value	NIST tolerances Min	NIST tolerances Max	Acceptable? (YES/NO)	NOTES
Length [L]	mm	54.839	54.84	55	54.7	55	YES	
Notch centering	mm	0.001	0.00	0	-0.2	0.2	YES	
Width [W]	mm	9.999	10.00	10	9.97	10.03	YES	
Thickness [B]	mm	10	10.00	10	9.97	10.03	YES	
Ligament [b]	mm	8.018	8.01	8	7.975	8.025	YES	
Notch radius [ρ]	mm	0.251	0.251	0.25	0.225	0.275	YES	
Notch angle [α]	°	44.45	44.45	45	44	46	YES	
Angle adj sides 1	°	90.02		90	89.85	90.15	YES	(*)
Angle adj sides 2	°	90.03		90	89.85	90.15	YES	(*)
Angle adj sides 3	°	90.01		90	89.85	90.15	YES	(*)
Angle adj sides 4	°	90.03		90	89.85	90.15	YES	(*)

Specimen 7

Dimension	Unit	Measured value	Corrected value	Nominal value	NIST tolerances Min	NIST tolerances Max	Acceptable? (YES/NO)	NOTES
Length [L]	mm	54.865	54.86	55	54.7	55	YES	
Notch centering	mm	0.01	0.01	0	-0.2	0.2	YES	
Width [W]	mm	9.994	9.99	10	9.97	10.03	YES	
Thickness [B]	mm	10.007	10.00	10	9.97	10.03	YES	

Ligament [b]	mm	8.05	8.05	8	7.975	8.025	NO	
Notch radius [ρ]	mm	0.265	0.265	0.25	0.225	0.275	YES	
Notch angle [α]	°	44.7	44.7	45	44	46	YES	
Angle adj sides 1	°	90.02		90	89.85	90.15	YES	(*)
Angle adj sides 2	°	89.97		90	89.85	90.15	YES	(*)
Angle adj sides 3	°	90.03		90	89.85	90.15	YES	(*)
Angle adj sides 4	°	90.01		90	89.85	90.15	YES	(*)

Specimen 8

Dimension	Unit	Measured value	Corrected value	Nominal value	NIST tolerances Min	NIST tolerances Max	Acceptable? (YES/NO)	NOTES
Length [L]	mm	54.848	54.85	55	54.7	55	YES	
Notch centering	mm	0.002	0.00	0	-0.2	0.2	YES	
Width [W]	mm	9.987	9.98	10	9.97	10.03	YES	
Thickness [B]	mm	10.01	10.01	10	9.97	10.03	YES	
Ligament [b]	mm	8.014	8.01	8	7.975	8.025	YES	
Notch radius [ρ]	mm	0.251	0.251	0.25	0.225	0.275	YES	
Notch angle [α]	°	44.66	44.66	45	44	46	YES	
Angle adj sides 1	°	90.01		90	89.85	90.15	YES	(*)
Angle adj sides 2	°	90.02		90	89.85	90.15	YES	(*)
Angle adj sides 3	°	89.93		90	89.85	90.15	YES	(*)
Angle adj sides 4	°	90.05		90	89.85	90.15	YES	(*)

Specimen 9

Dimension	Unit	Measured value	Corrected value	Nominal value	NIST tolerances Min	NIST tolerances Max	Acceptable? (YES/NO)	NOTES
Length [L]	mm	54.862	54.86	55	54.7	55	YES	
Notch centering	mm	0.007	0.01	0	-0.2	0.2	YES	
Width [W]	mm	9.995	9.99	10	9.97	10.03	YES	
Thickness [B]	mm	10.007	10.00	10	9.97	10.03	YES	
Ligament [b]	mm	8.023	8.02	8	7.975	8.025	YES	
Notch radius [ρ]	mm	0.251	0.251	0.25	0.225	0.275	YES	
Notch angle [α]	°	44.24	44.24	45	44	46	YES	
Angle adj sides 1	°	90.02		90	89.85	90.15	YES	(*)
Angle adj sides 2	°	90.03		90	89.85	90.15	YES	(*)
Angle adj sides 3	°	89.92		90	89.85	90.15	YES	(*)
Angle adj sides 4	°	90.12		90	89.85	90.15	YES	(*)

Specimen 10

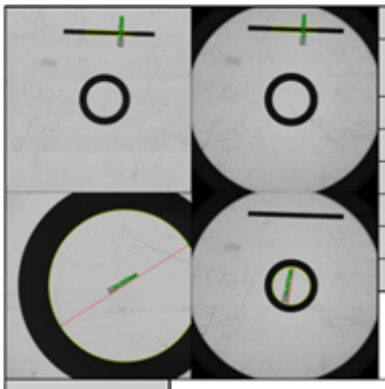
Dimension	Unit	Measured value	Corrected value	Nominal value	NIST tolerances Min	NIST tolerances Max	Acceptable? (YES/NO)	NOTES
Length [L]	mm	54.847	54.84	55	54.7	55	YES	
Notch centering	mm	0.01	0.01	0	-0.2	0.2	YES	
Width [W]	mm	9.992	9.99	10	9.97	10.03	YES	
Thickness [B]	mm	10.004	10.00	10	9.97	10.03	YES	
Ligament [b]	mm	8.01	8.01	8	7.975	8.025	YES	
Notch radius [ρ]	mm	0.251	0.251	0.25	0.225	0.275	YES	
Notch angle [α]	°	44.43	44.43	45	44	46	YES	
Angle adj sides 1	°	90.02		90	89.85	90.15	YES	(*)
Angle adj sides 2	°	90.05		90	89.85	90.15	YES	(*)
Angle adj sides 3	°	90.05		90	89.85	90.15	YES	(*)
Angle adj sides 4	°	89.99		90	89.85	90.15	YES	(*)

Appendix B. Digital Optical Comparator Recertification Program Report (2023)

NIST National Institute of Standards and Technology U.S. Department of Commerce

Sig.	

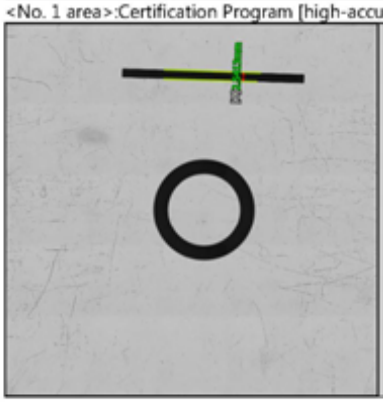
Part report



Program name	Recertification Program (plug + ring)
Measurement Date and Time	10/13/2023 11:35:10 AM
Lot No.	Recertification 10/13/2023
Serial Counter	0001
Name	
Item name	
Measurement device	
Overall result	OK

Remarks	

<No. 1 area>:Certification Program [high-accuracy, plug]



Judgment result	OK

[Measurement results]

No.	measurement item	mes. value	units	design val.	upper limit	lower Limit	res.
1	LN-LN001	2.5413	mm	2.5400	0.0020	-0.0020	OK

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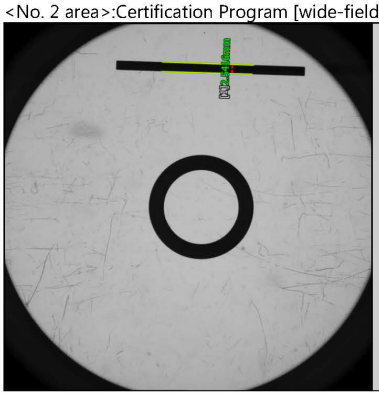
<No. 2 area>:Certification Program [wide-field, plug]

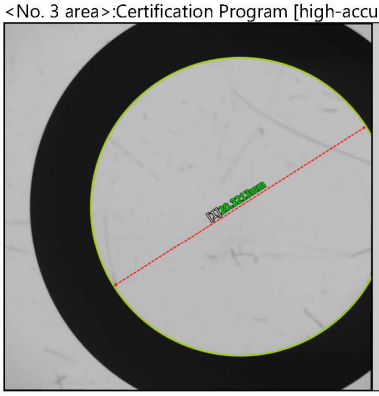


Judgment result: OK

[Measurement results]

No.	measurement item	mes. value	units	design val.	upper limit	lower Limit	res.
1	LN-LN001	2.5416	mm	2.5400	0.0050	-0.0050	OK

<No. 3 area>:Certification Program [high-accuracy, ring]



Judgment result: OK

[Measurement results]

No.	measurement item	mes. value	units	design val.	upper limit	lower Limit	res.
1	DIA001	20.3213	mm	20.3200	0.0084	-0.0084	OK

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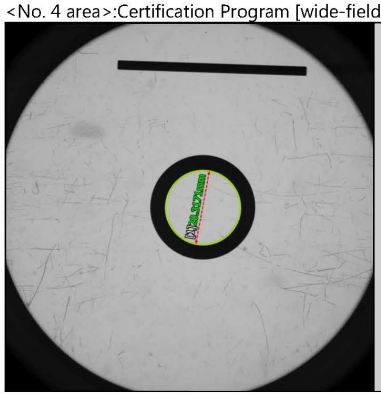
<No. 4 area>:Certification Program [wide-field, ring]



Judgment result | OK

[Measurement results]

No.	measurement item	mes. value	units	design val.	upper limit	lower Limit	res.
1	DIA001	20.3171	mm	20.3200	0.0080	-0.0080	OK

Appendix C. Recertification Report (2023)

NIST
National Institute of Standards and Technology
U.S. Department of Commerce

[redacted] Re-Certification (2023)

Linear Dimensions

Artifacts: [redacted] Gage Blocks (Set No.010412), Grade: 2 Date: October 17, 2023

Nominal dimension (mm)	Measurements (mm) #1	#2	#3	#4	#5	Deviation (µm)
0.5	0.505	0.504	0.505	0.505	0.505	5
1	1.007	1.007	1.008	1.008	1.007	7
1.5	1.507	1.507	1.504	1.504	1.504	5
2	2.005	2.008	2.006	2.004	2.004	5
3	3.005	3.004	3.006	3.005	3.006	5
5	5.005	5.005	5.005	5.006	5.006	5
7.5	7.505	7.506	7.505	7.505	7.505	5
10	10.004	10.004	10.004	10.004	10.004	4
20	20.005	20.006	20.006	20.006	20.006	6
40	40.005	40.004	40.007	40.006	40.004	5
60	60.000	60.002	60.003	60.003	60.000	2
80	80.001	80.002	80.001	80.003	80.004	2

Angles

Artifacts: [redacted] Angle Blocks (set of 10) Date: December 15, 2023

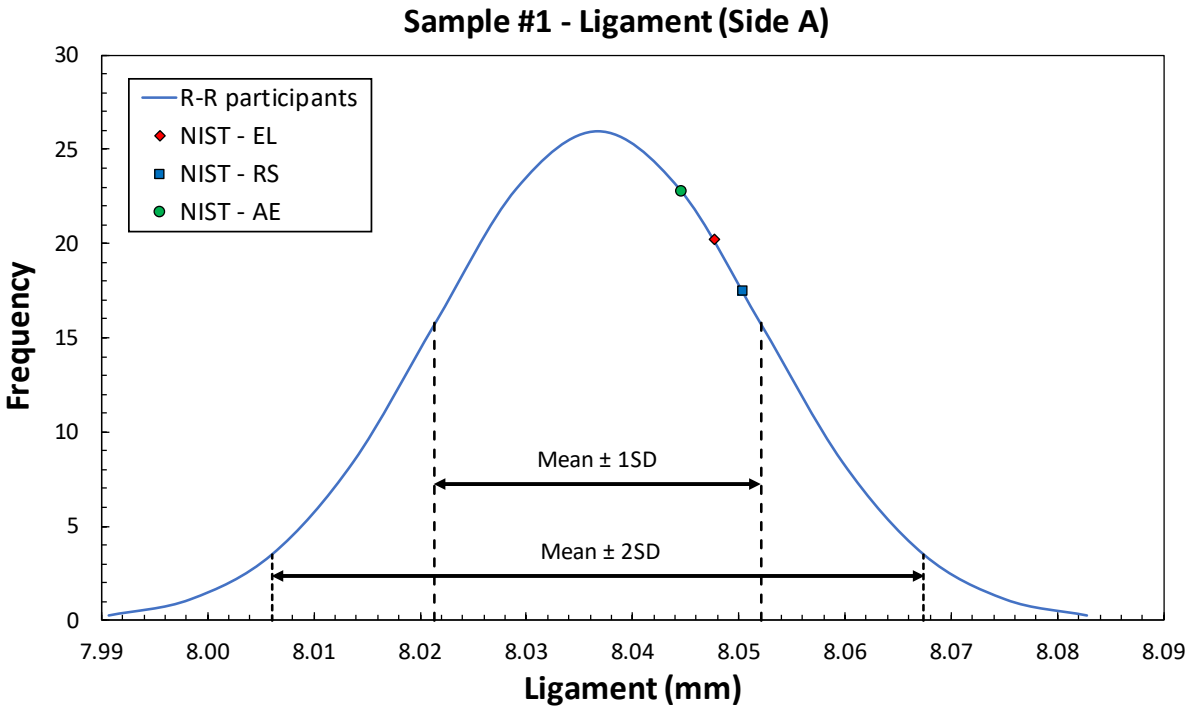
Nominal value (°)	Measurements (°) #1	#2	#3	#4	#5	Deviation (°)
15	15.00	14.98	14.98	14.98	14.99	-0.01
30	30.02	30.02	30.01	30.01	30.00	0.01
45	44.99	44.99	44.99	45.00	45.00	-0.01

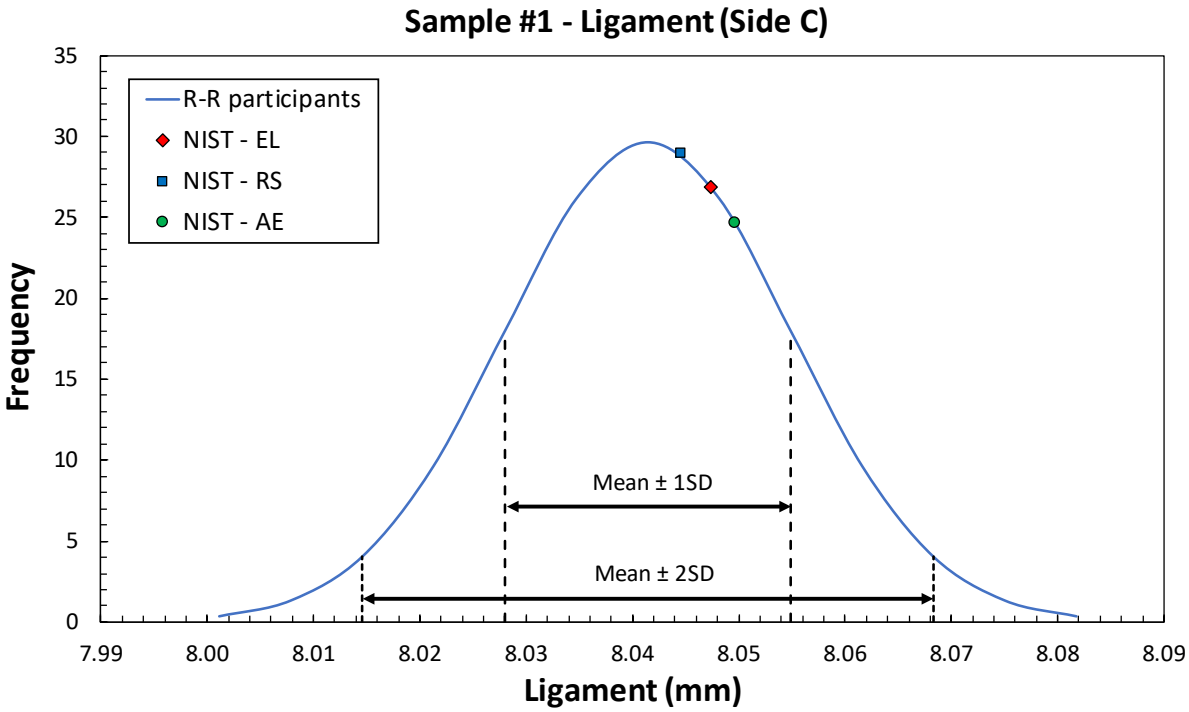
Radius

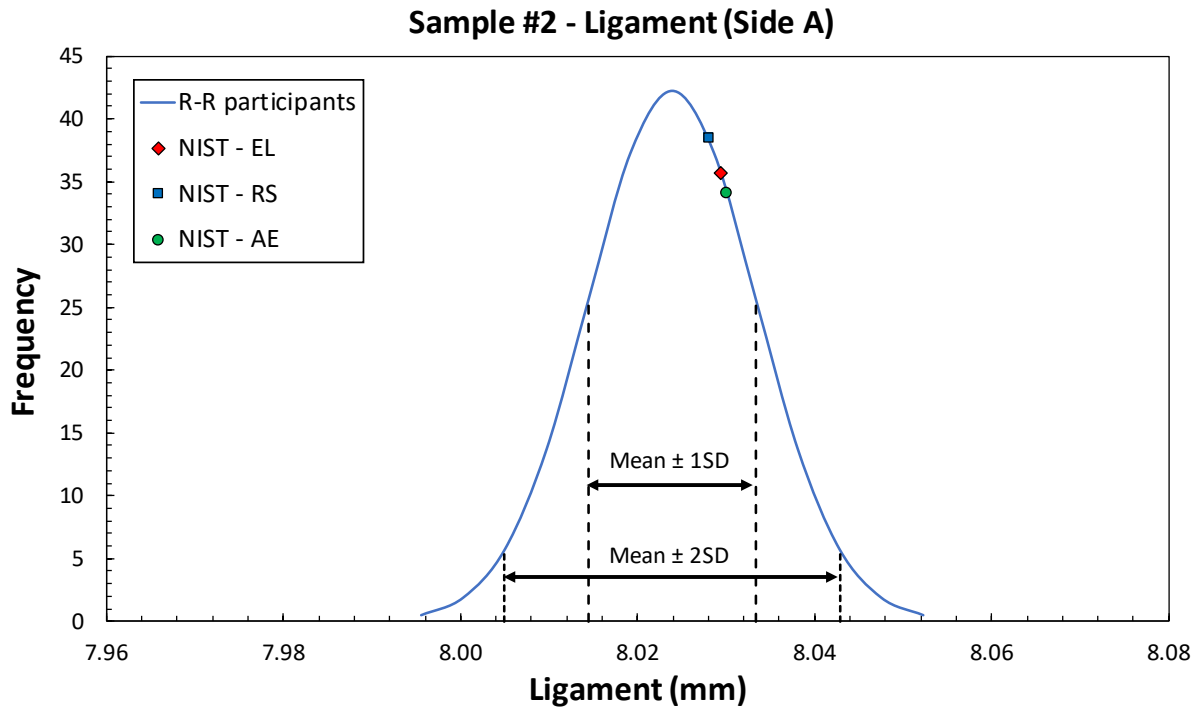
Artifacts: [redacted] Decimal Radius Gage 0.100" Date: December 18, 2023

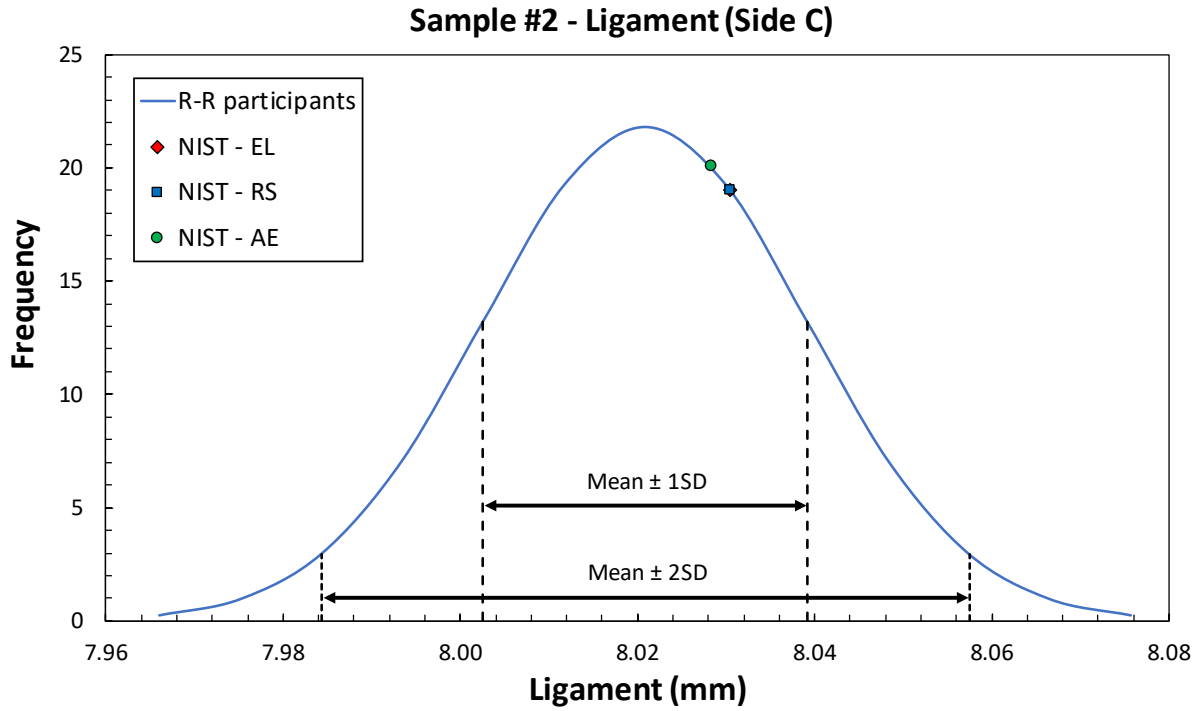
radius (mm)	#1	#2	#3	#4	#5	(mm)
0.254	0.260	0.260	0.261	0.262	0.260	0.007

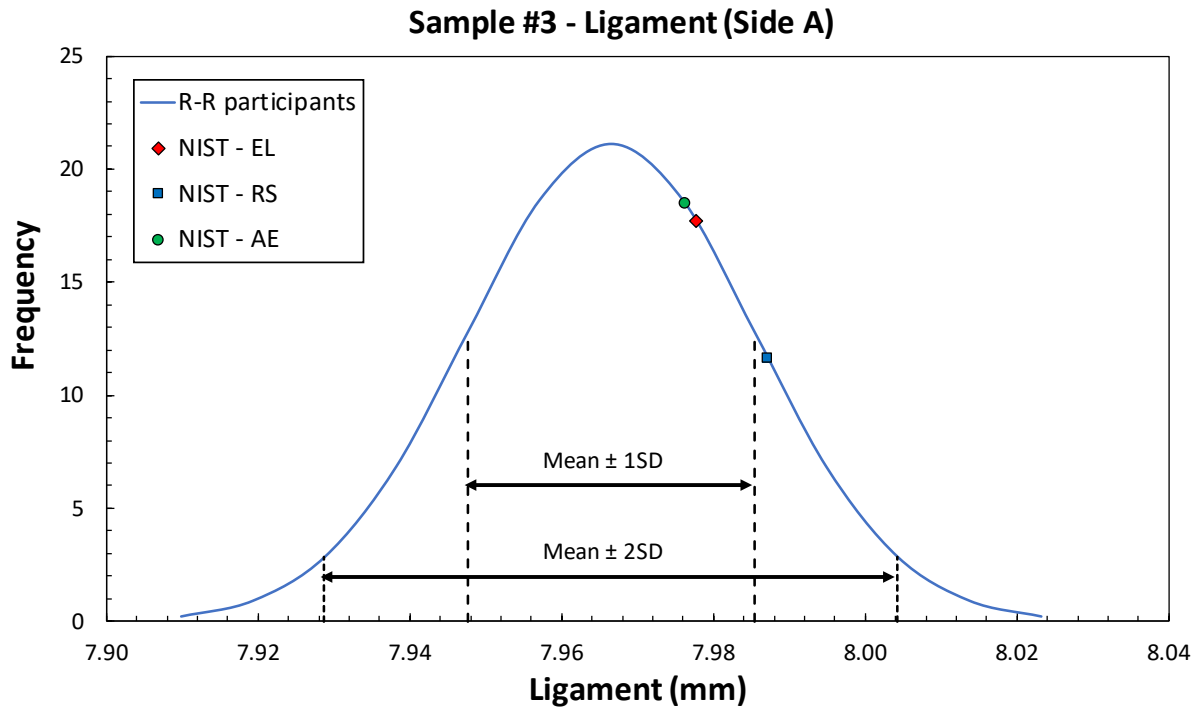
Appendix D. Comparisons between NIST measurements and ILS results

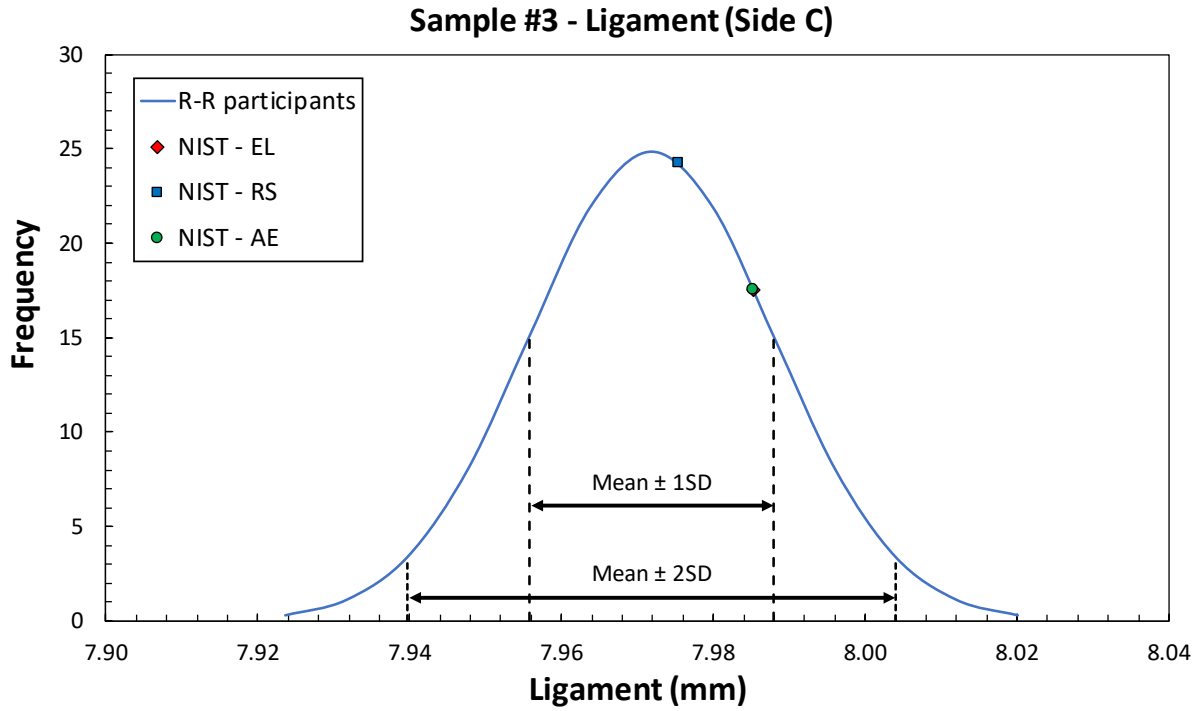


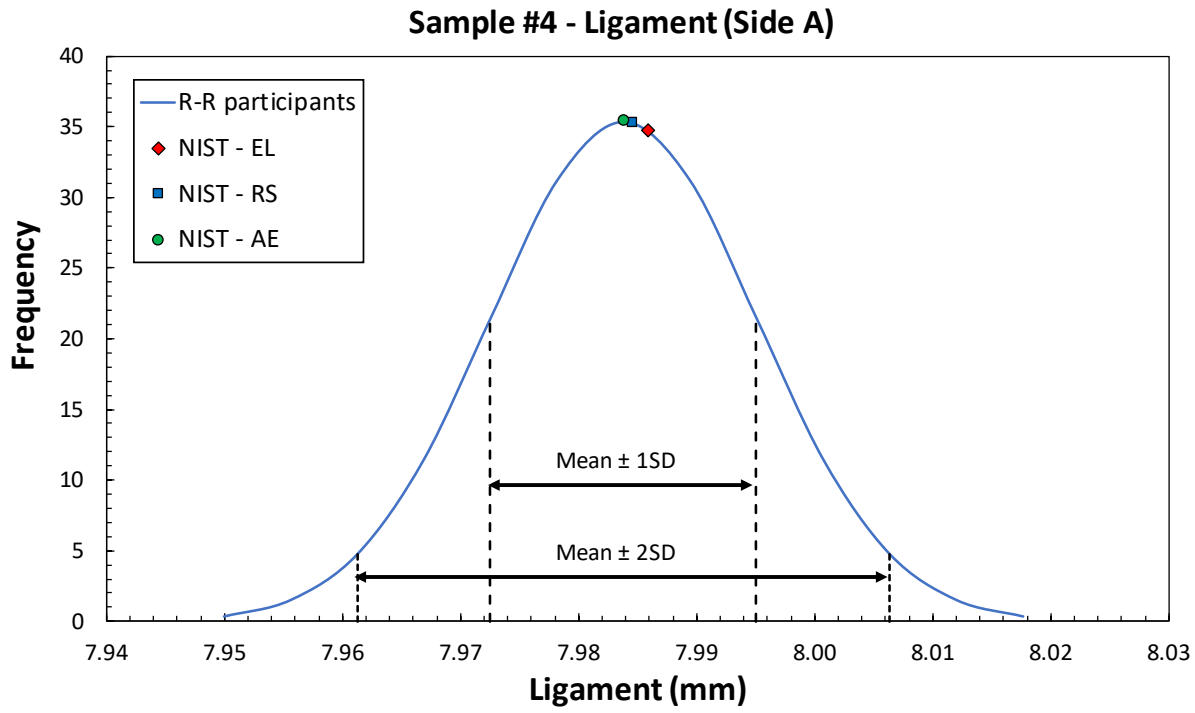


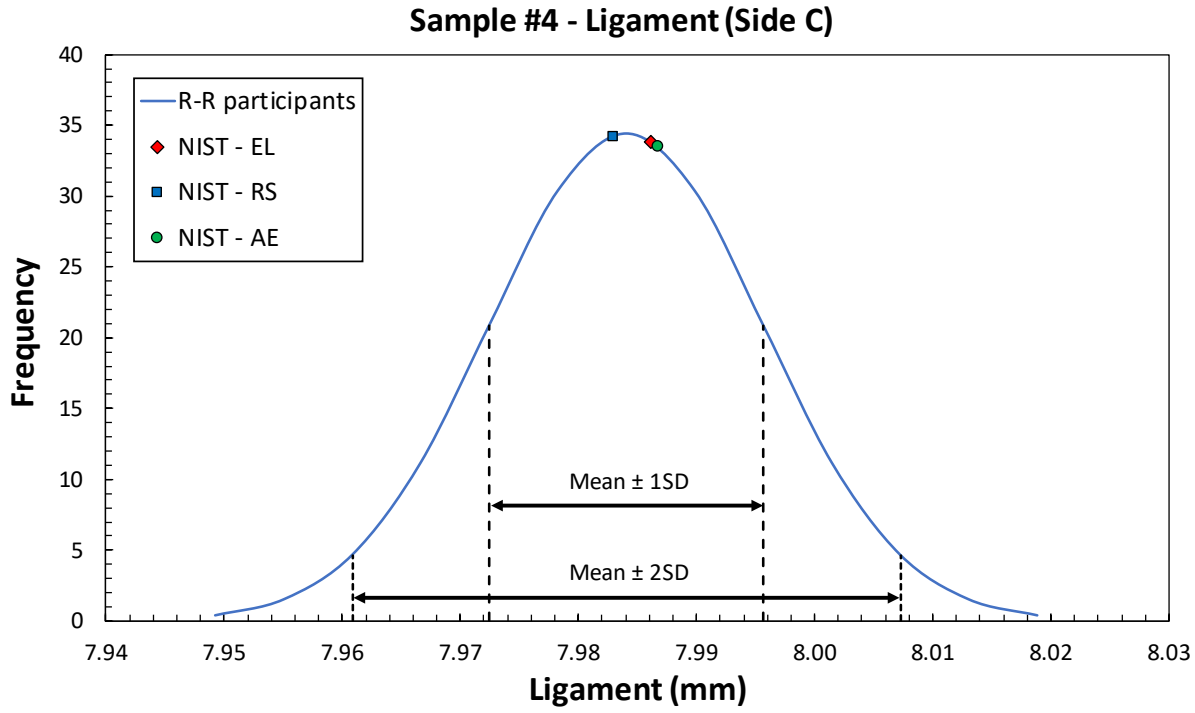

Sample #2 - Ligament (Side A)
R-R participants
NIST - EL
NIST - RS
NIST - AE
Mean ± 1SD
Mean ± 2SD
Frequency
Ligament (mm)
0
5
10
15
20
25
30
35
40
45
7.96
7.98
8.00
8.02
8.04
8.06
8.08

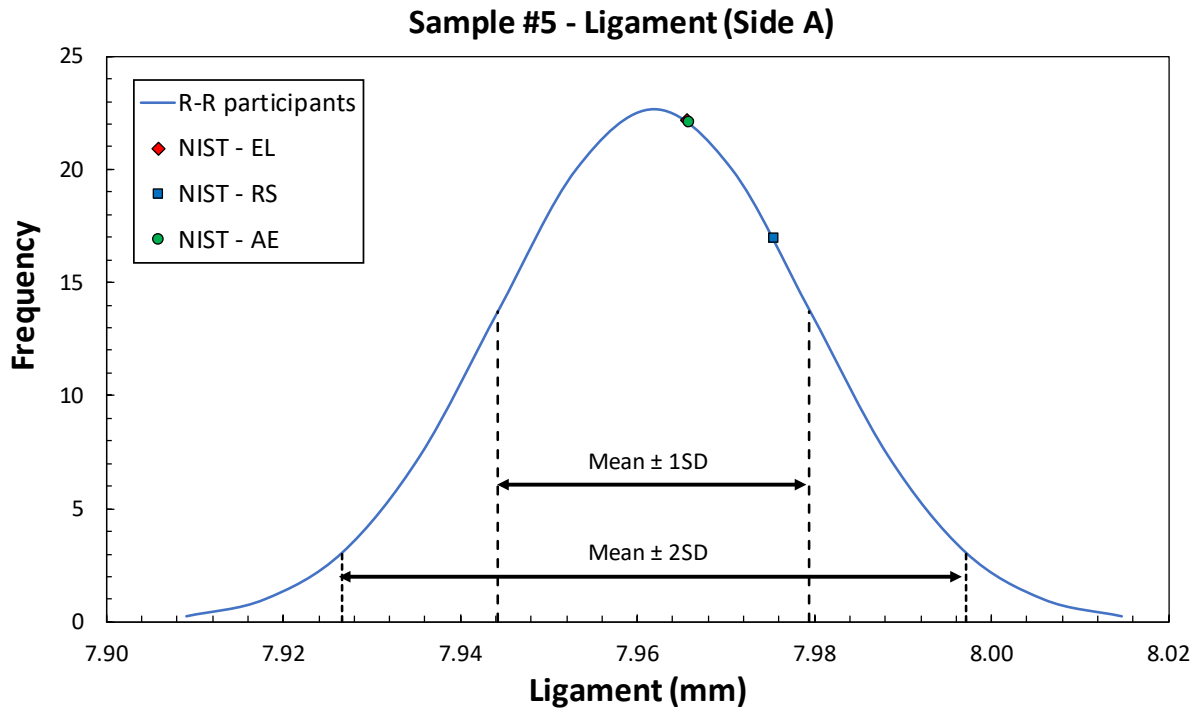

Sample #2 - Ligament (Side C)
R-R participants
NIST - EL
NIST - RS
NIST - AE
Mean ± 1SD
Mean ± 2SD
Frequency
Ligament (mm)
0
5
10
15
20
25
7.96
7.98
8.00
8.02
8.04
8.06
8.08

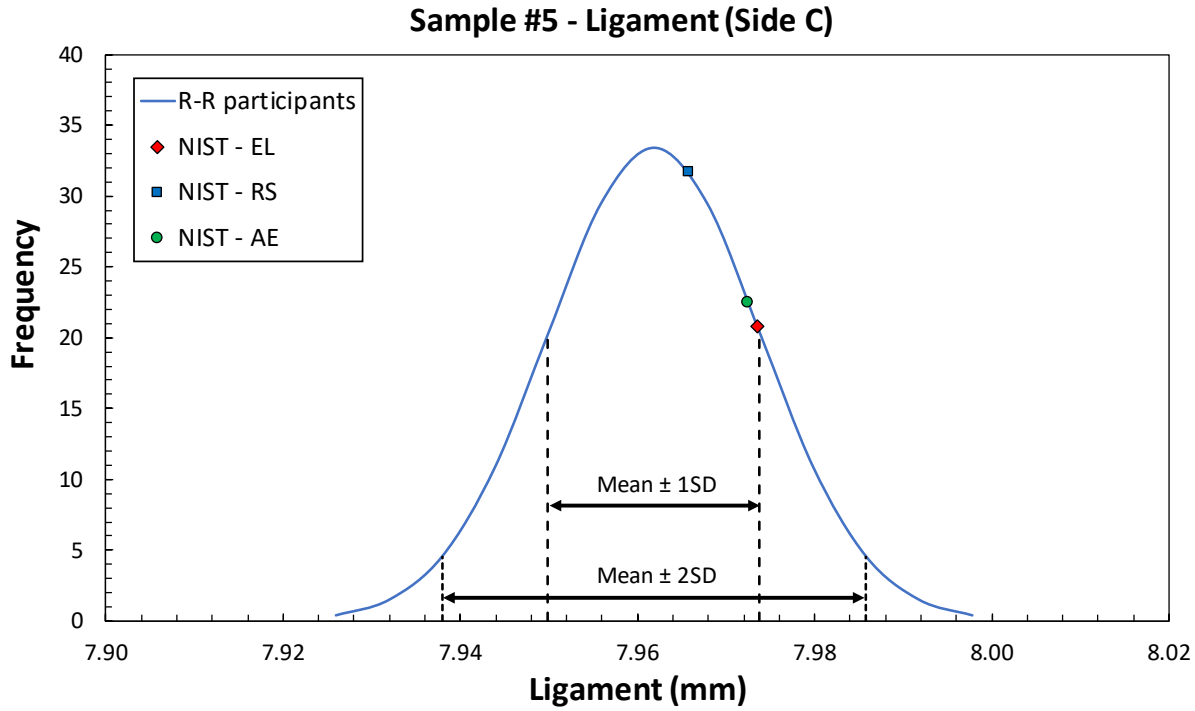

Sample #3 - Ligament (Side A)
R-R participants
NIST - EL
NIST - RS
NIST - AE
Mean ± 1SD
Mean ± 2SD
Frequency
Ligament (mm)
0
5
10
15
20
25
7.90
7.92
7.94
7.96
7.98
8.00
8.02
8.04

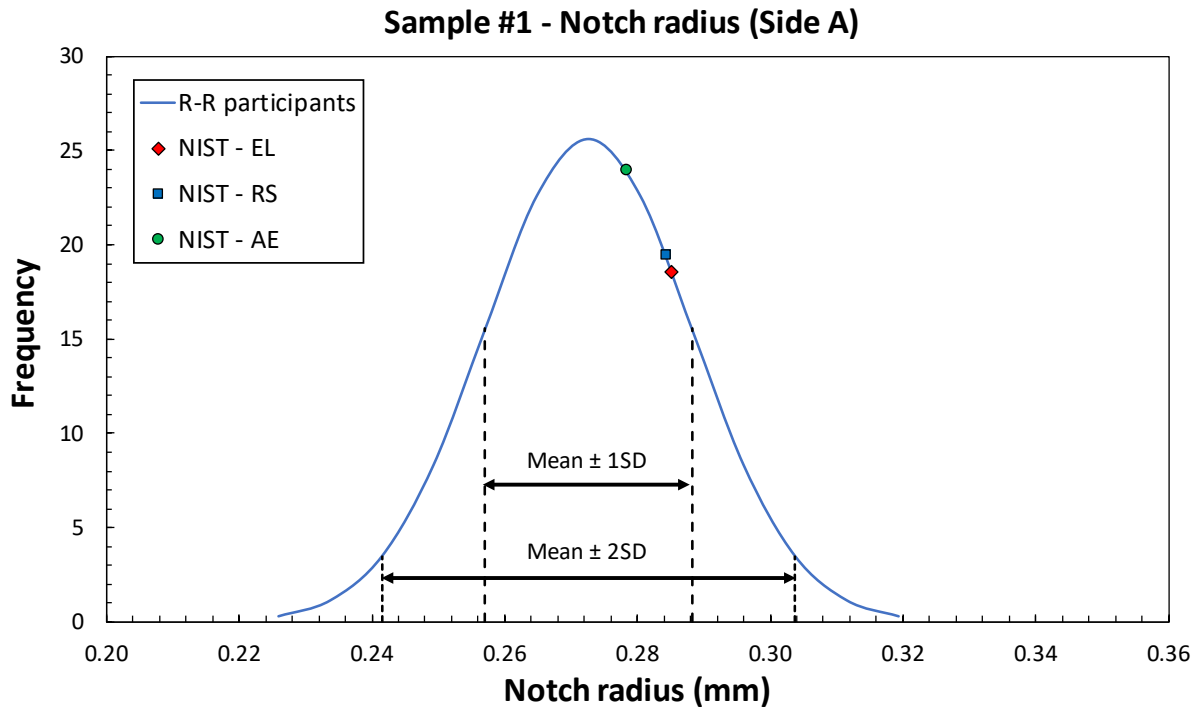

Sample #3 - Ligament (Side C)
R-R participants
NIST - EL
NIST - RS
NIST - AE
Mean ± 1SD
Mean ± 2SD
Frequency
Ligament (mm)
0
5
10
15
20
25
30
7.90
7.92
7.94
7.96
7.98
8.00
8.02
8.04

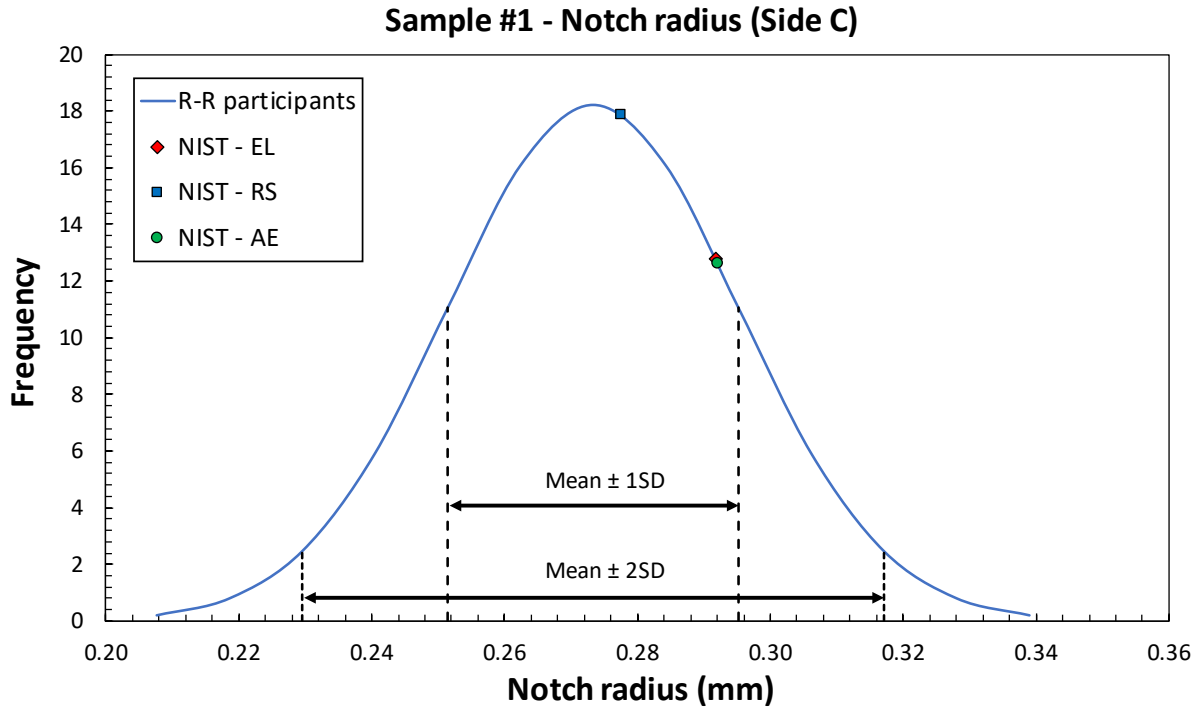

Sample #4 - Ligament (Side A)
R-R participants
NIST - EL
NIST - RS
NIST - AE
Mean ± 1SD
Mean ± 2SD
Frequency
Ligament (mm)
0
5
10
15
20
25
30
35
40
7.94
7.95
7.96
7.97
7.98
7.99
8.00
8.01
8.02
8.03

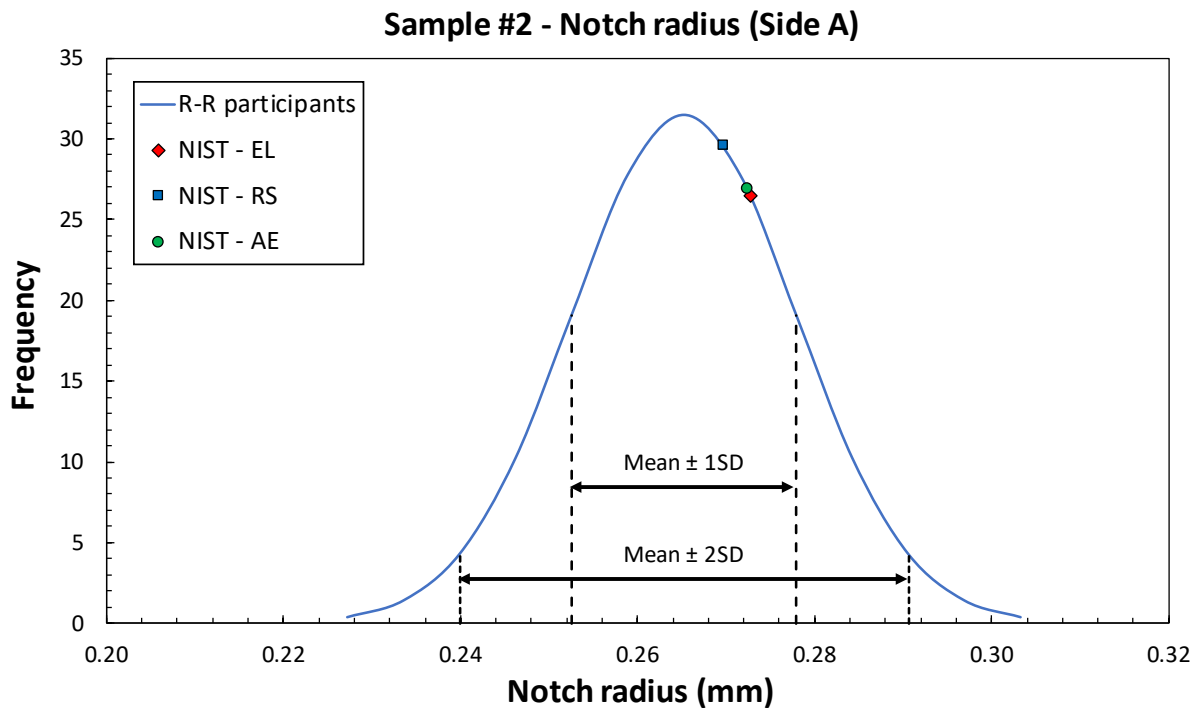

Sample #4 - Ligament (Side C)
R-R participants
NIST - EL
NIST - RS
NIST - AE
Mean ± 1SD
Mean ± 2SD
Frequency
Ligament (mm)
0
5
10
15
20
25
30
35
40
7.94
7.95
7.96
7.97
7.98
7.99
8.00
8.01
8.02
8.03

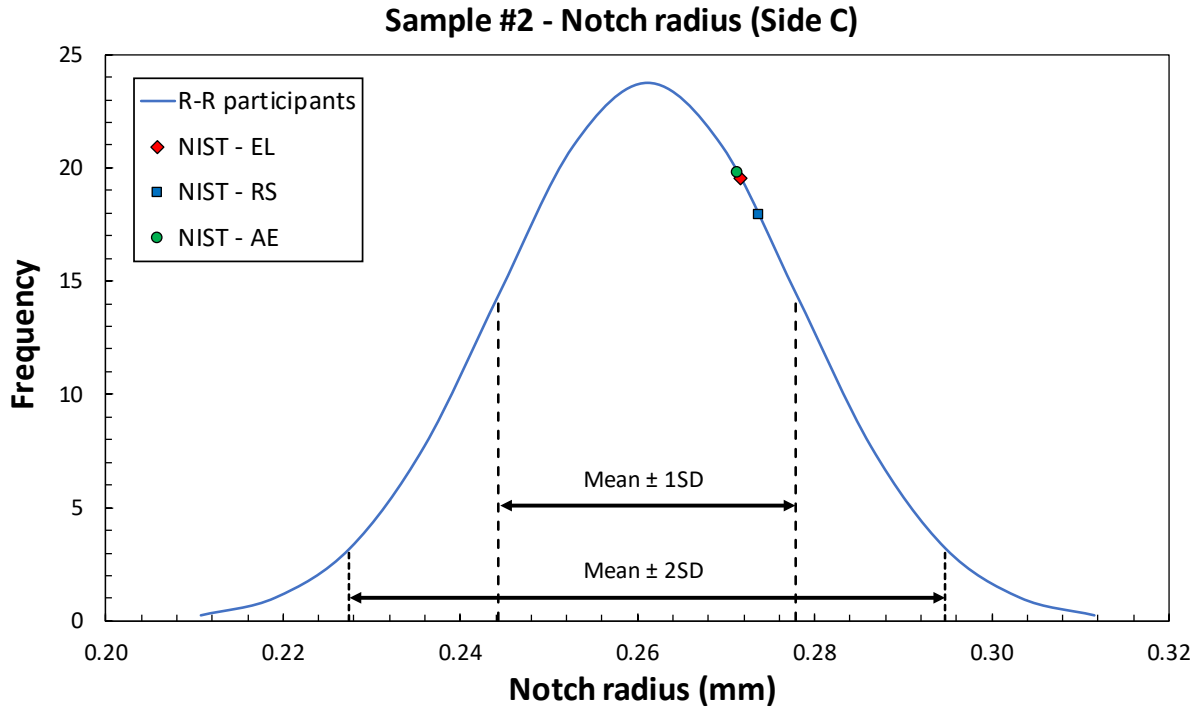

Sample #5 - Ligament (Side A)
R-R participants
NIST - EL
NIST - RS
NIST - AE
Mean ± 1SD
Mean ± 2SD
Frequency
Ligament (mm)
0
5
10
15
20
25
7.90
7.92
7.94
7.96
7.98
8.00
8.02

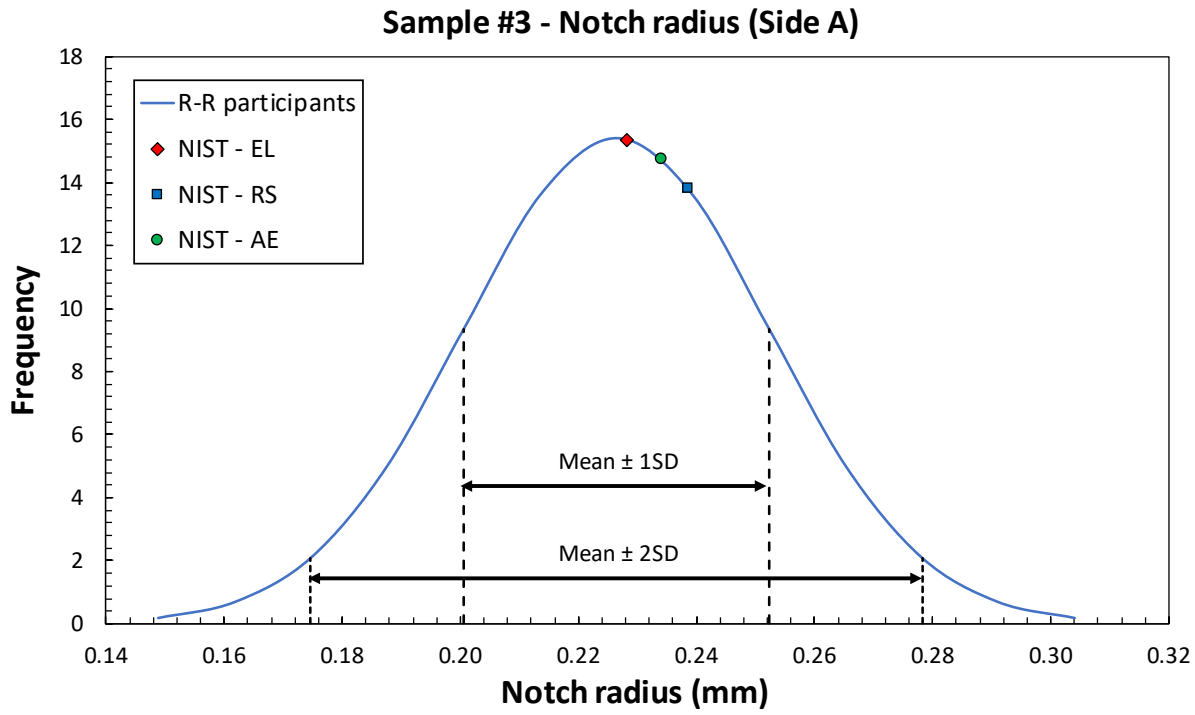

Sample #5 - Ligament (Side C)
R-R participants
NIST - EL
NIST - RS
NIST - AE
Mean ± 1SD
Mean ± 2SD
Frequency
Ligament (mm)
0
5
10
15
20
25
30
35
40
7.90
7.92
7.94
7.96
7.98
8.00
8.02

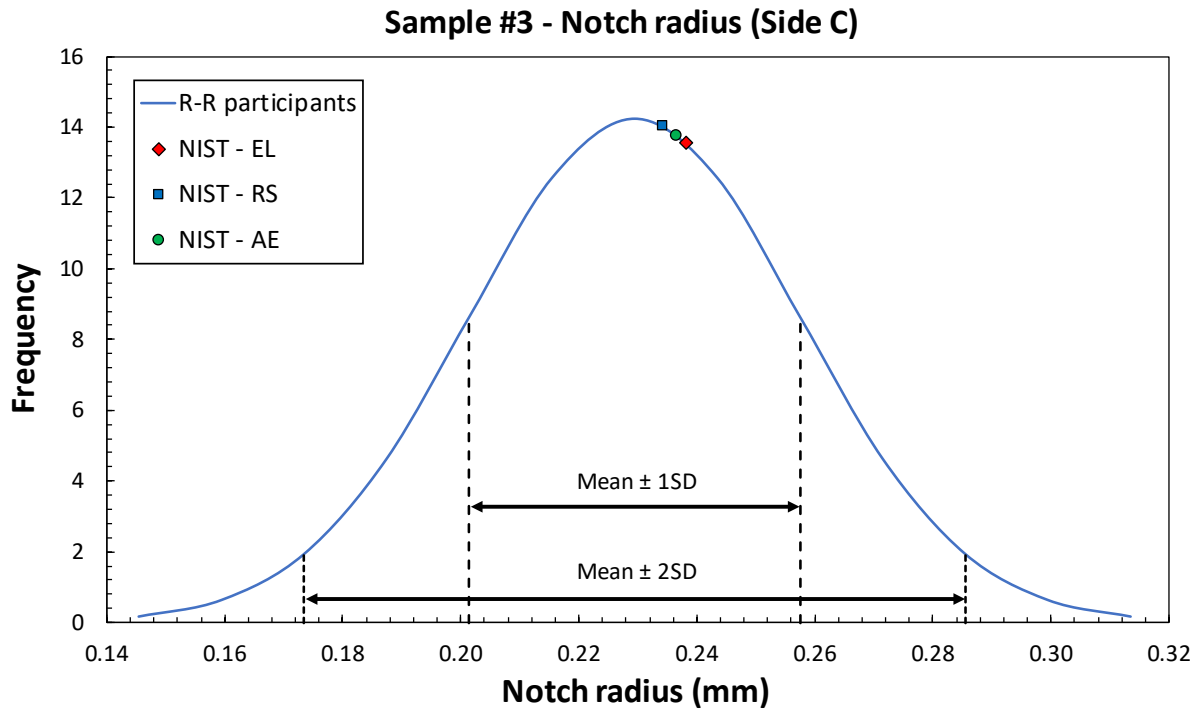

Sample #1 - Notch radius (Side A)
R-R participants
NIST - EL
NIST - RS
NIST - AE
Mean ± 1SD
Mean ± 2SD
Frequency
Notch radius (mm)
0
5
10
15
20
25
30
0.20
0.22
0.24
0.26
0.28
0.30
0.32
0.34
0.36

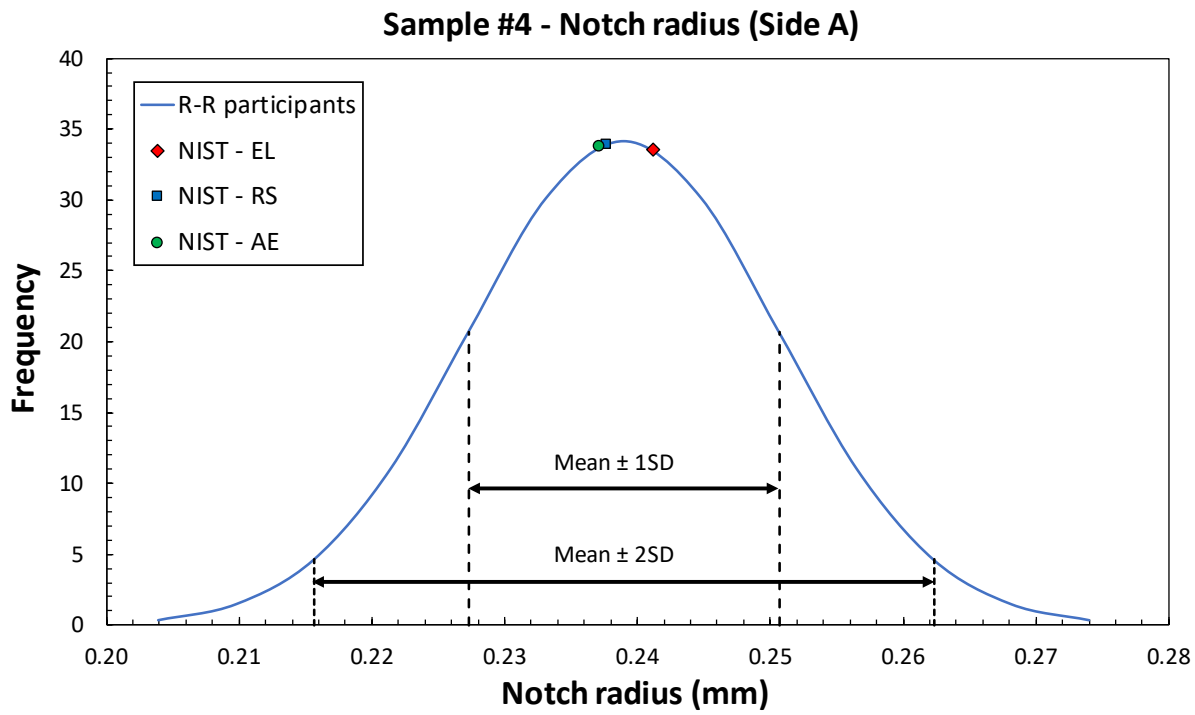

Sample #1 - Notch radius (Side C)
R-R participants
NIST - EL
NIST - RS
NIST - AE
Mean ± 1SD
Mean ± 2SD
Frequency
Notch radius (mm)
0
2
4
6
8
10
12
14
16
18
20
0.20
0.22
0.24
0.26
0.28
0.30
0.32
0.34
0.36

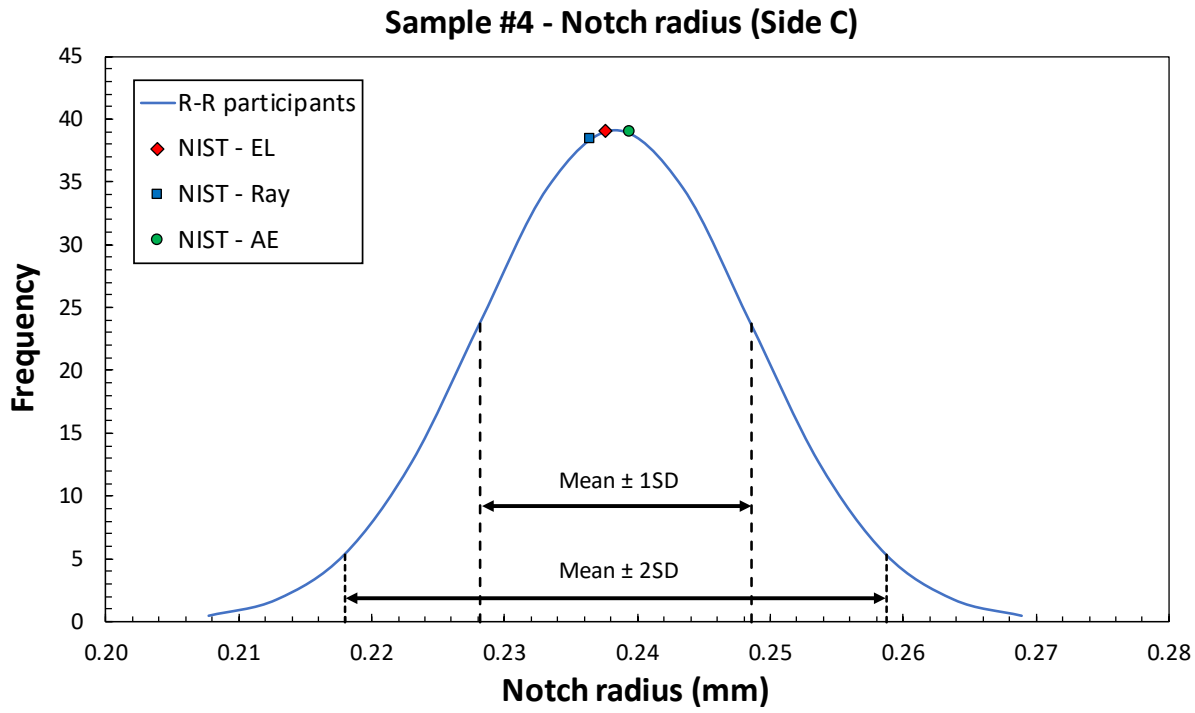

Sample #2 - Notch radius (Side A)
R-R participants
NIST - EL
NIST - RS
NIST - AE
Mean ± 1SD
Mean ± 2SD
Frequency
Notch radius (mm)
0
5
10
15
20
25
30
35
0.20
0.22
0.24
0.26
0.28
0.30
0.32

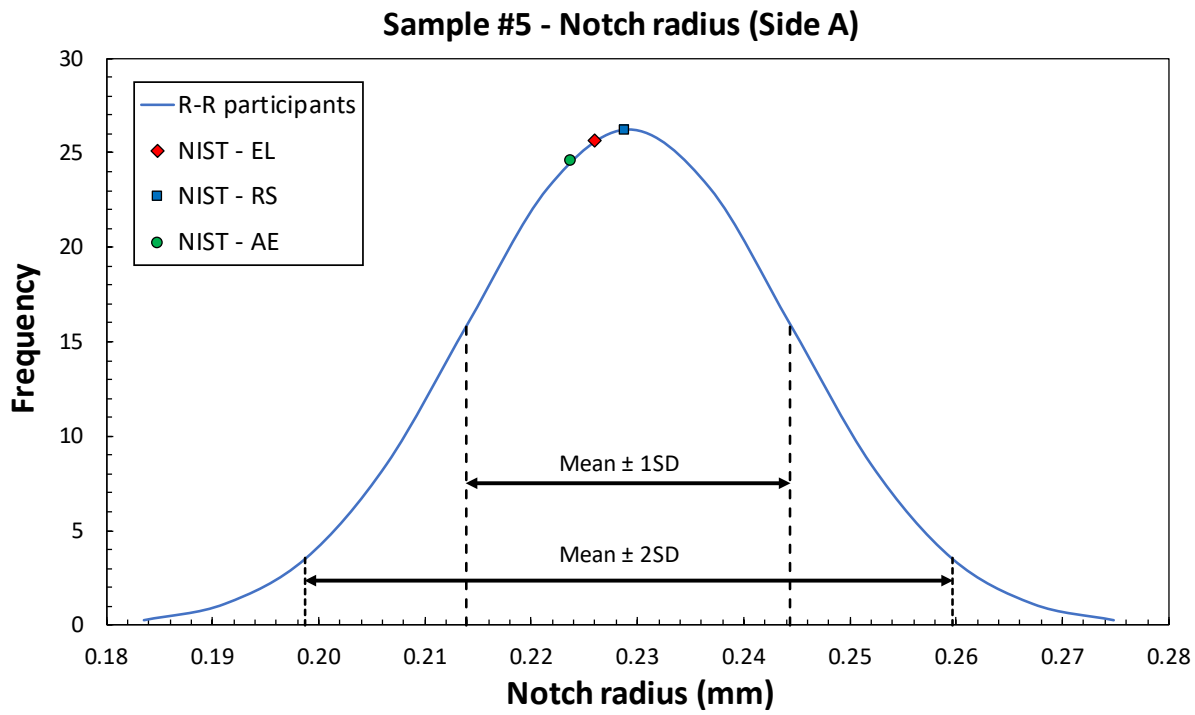

Sample #2 - Notch radius (Side C)
R-R participants
NIST - EL
NIST - RS
NIST - AE
Mean ± 1SD
Mean ± 2SD
Frequency
Notch radius (mm)
0
5
10
15
20
25
0.20
0.22
0.24
0.26
0.28
0.30
0.32

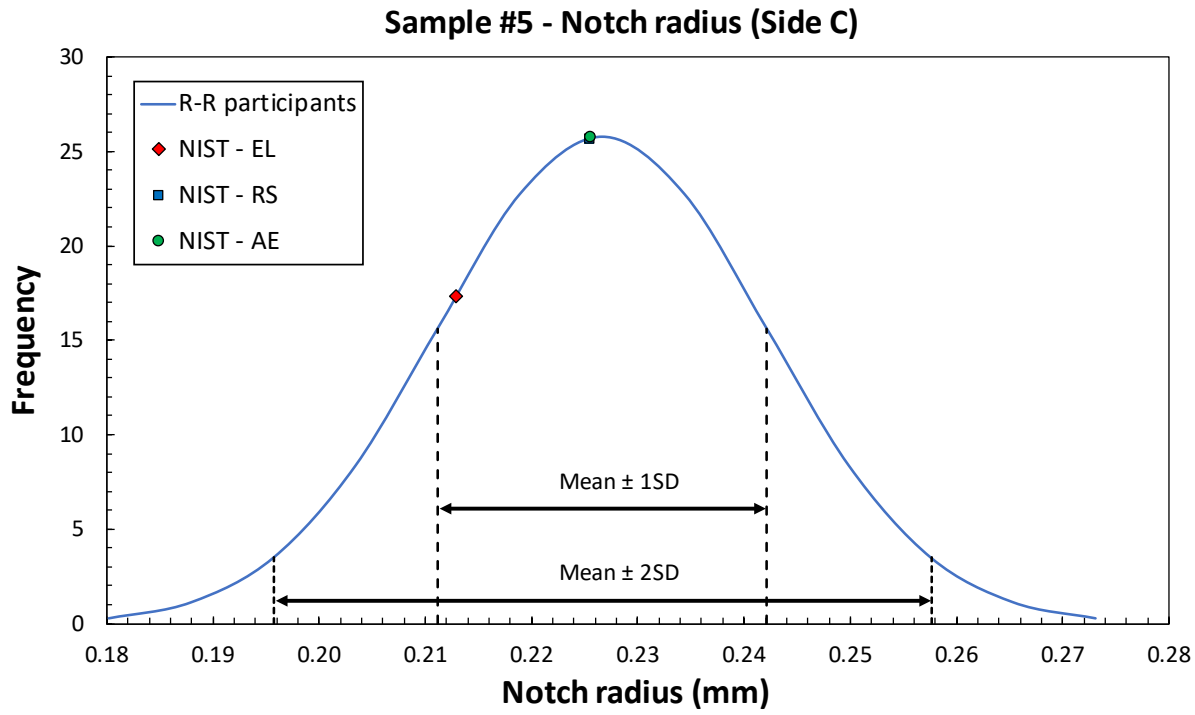

Sample #3 - Notch radius (Side A)
R-R participants
NIST - EL
NIST - RS
NIST - AE
Mean ± 1SD
Mean ± 2SD
Frequency
Notch radius (mm)
0
2
4
6
8
10
12
14
16
18
0.14
0.16
0.18
0.20
0.22
0.24
0.26
0.28
0.30
0.32

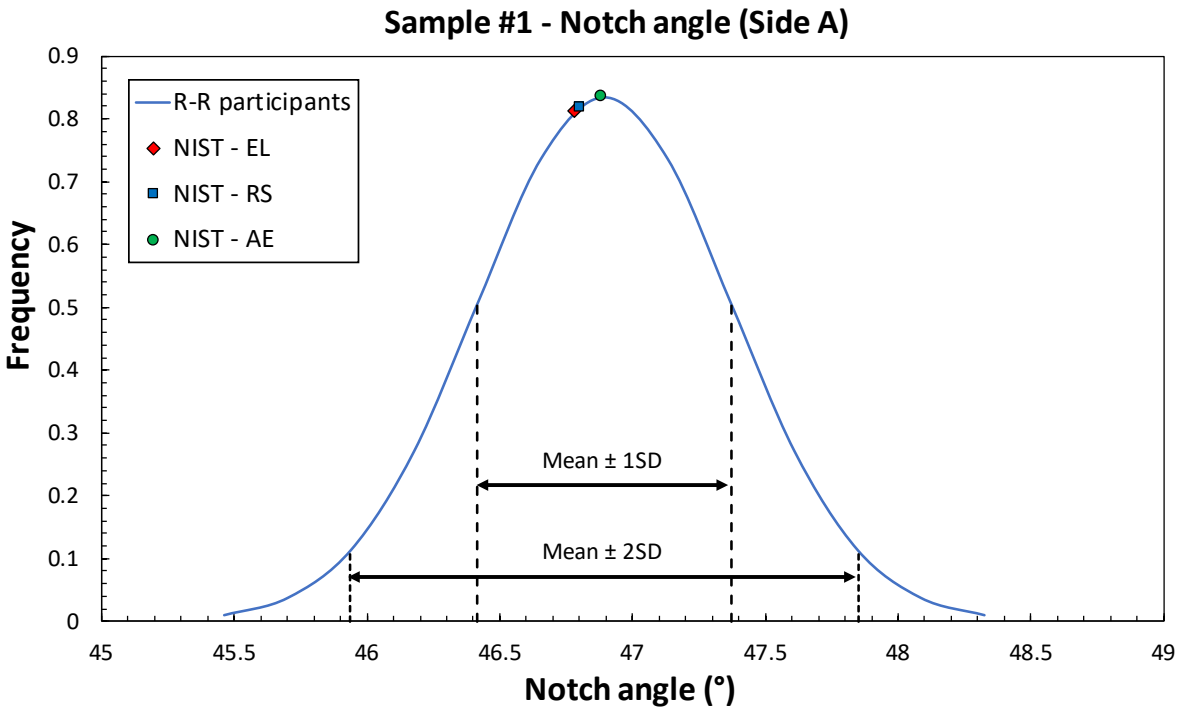

Sample #3 - Notch radius (Side C)
R-R participants
NIST - EL
NIST - RS
NIST - AE
Mean ± 1SD
Mean ± 2SD
Frequency
Notch radius (mm)
0
2
4
6
8
10
12
14
16
0.14
0.16
0.18
0.20
0.22
0.24
0.26
0.28
0.30
0.32

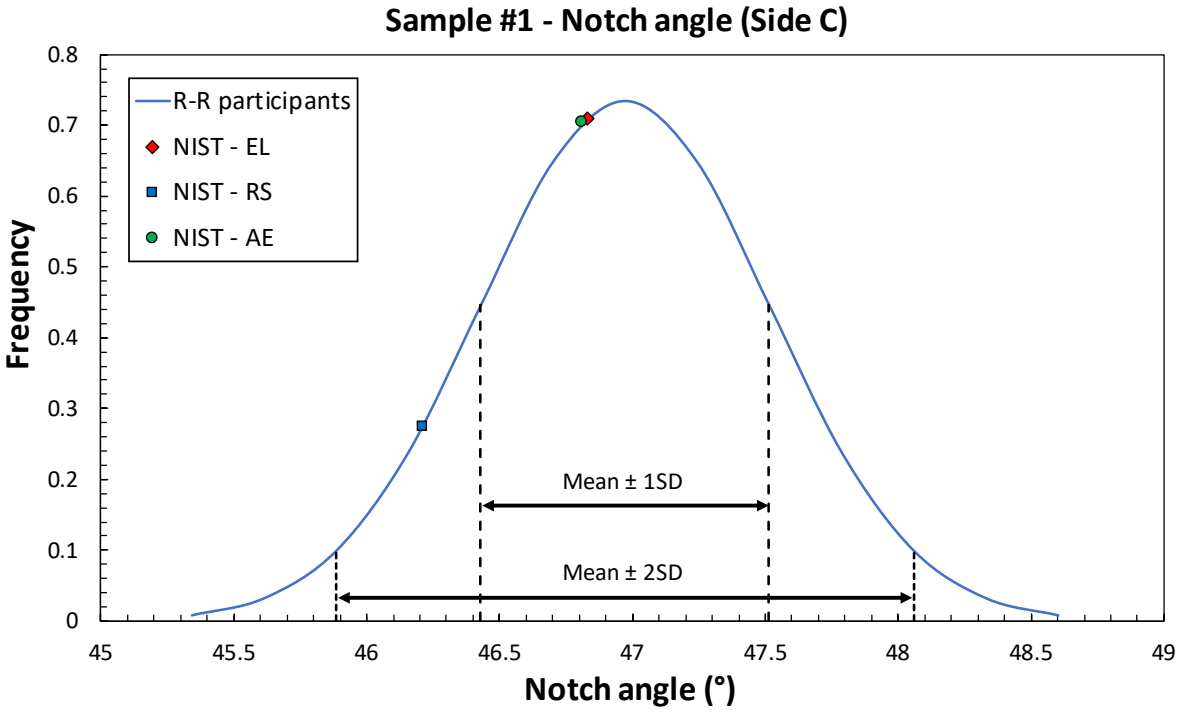

Sample #4 - Notch radius (Side A)
R-R participants
NIST - EL
NIST - RS
NIST - AE
Mean ± 1SD
Mean ± 2SD
Frequency
Notch radius (mm)
0
5
10
15
20
25
30
35
40
0.20
0.21
0.22
0.23
0.24
0.25
0.26
0.27
0.28

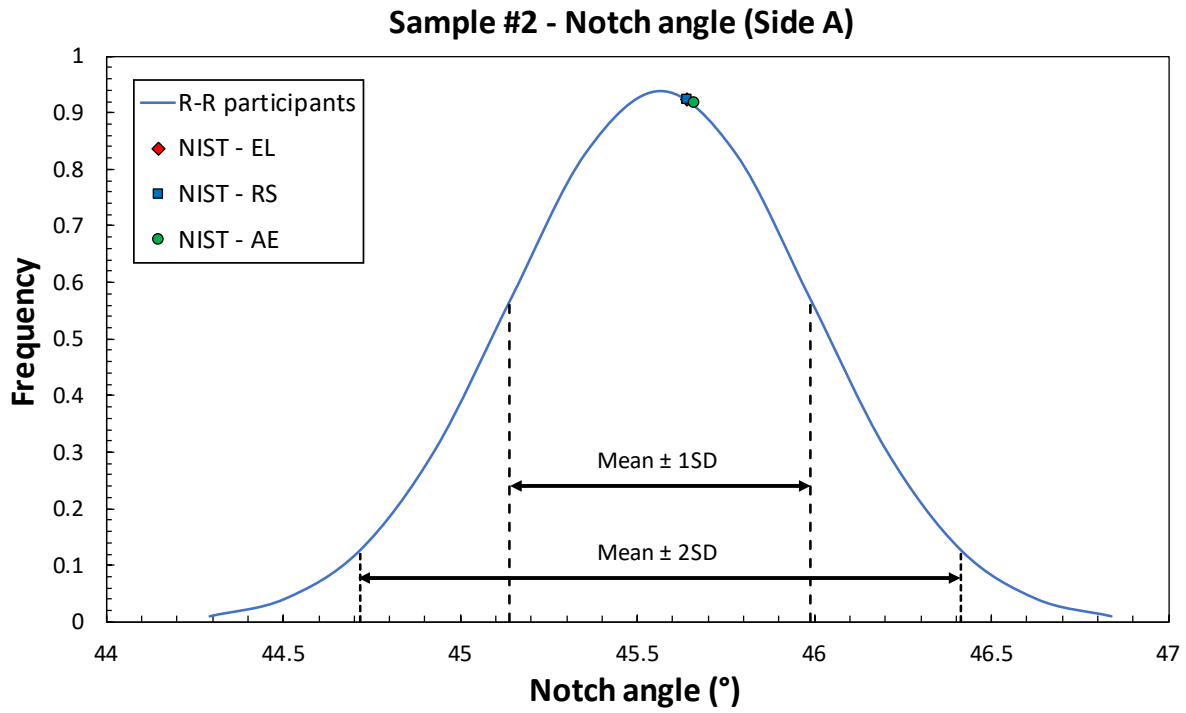

Sample #4 - Notch radius (Side C)
R-R participants
NIST - EL
NIST - Ray
NIST - AE
Mean ± 1SD
Mean ± 2SD
Frequency
Notch radius (mm)
0
5
10
15
20
25
30
35
40
45
0.20
0.21
0.22
0.23
0.24
0.25
0.26
0.27
0.28

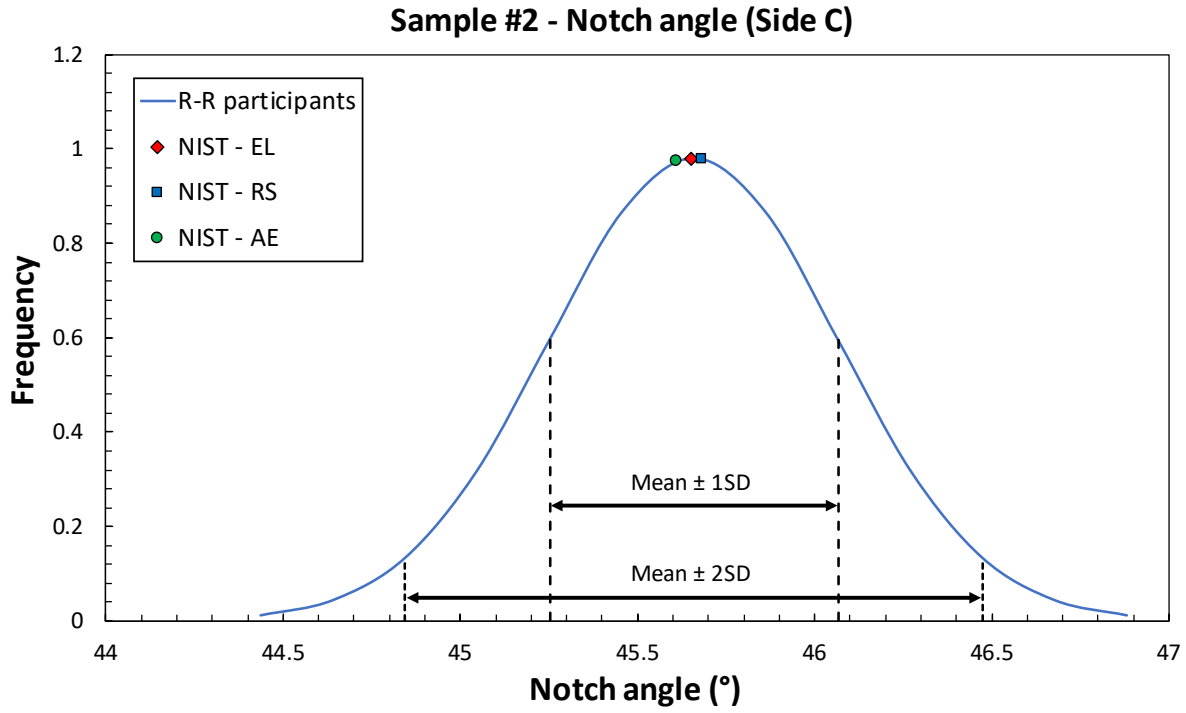

Sample #5 - Notch radius (Side A)
R-R participants
NIST - EL
NIST - RS
NIST - AE
Mean ± 1SD
Mean ± 2SD
Frequency
Notch radius (mm)
0
5
10
15
20
25
30
0.18
0.19
0.20
0.21
0.22
0.23
0.24
0.25
0.26
0.27
0.28

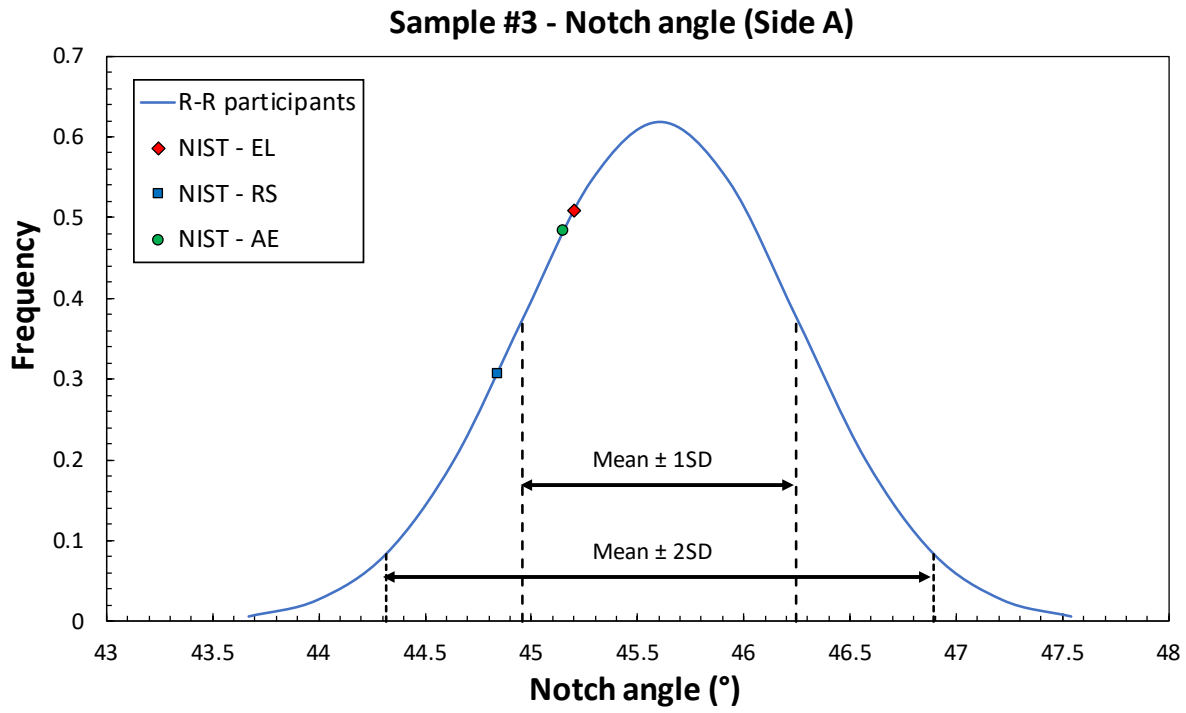

Sample #5 - Notch radius (Side C)
R-R participants
NIST - EL
NIST - RS
NIST - AE
Mean ± 1SD
Mean ± 2SD
Frequency
Notch radius (mm)
0
5
10
15
20
25
30
0.18
0.19
0.20
0.21
0.22
0.23
0.24
0.25
0.26
0.27
0.28

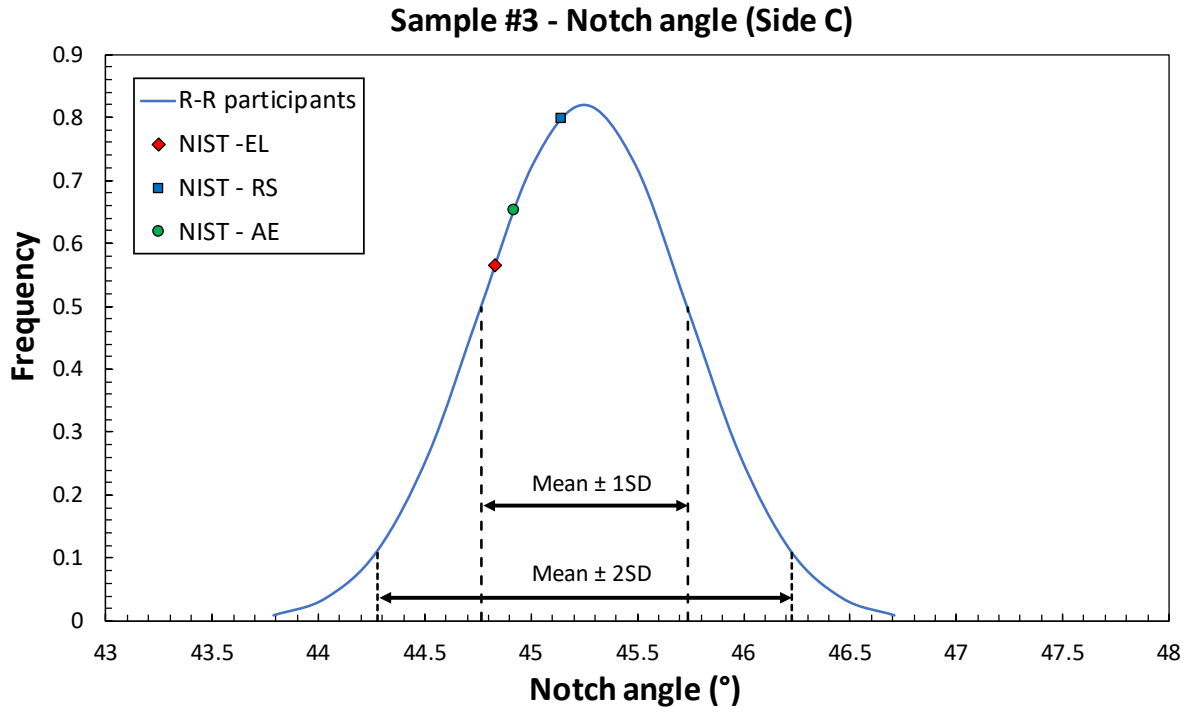

Sample #1 - Notch angle (Side A)
R-R participants
NIST - EL
NIST - RS
NIST - AE
Mean ± 1SD
Mean ± 2SD
Frequency
Notch angle (°)
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
45
45.5
46
46.5
47
47.5
48
48.5
49

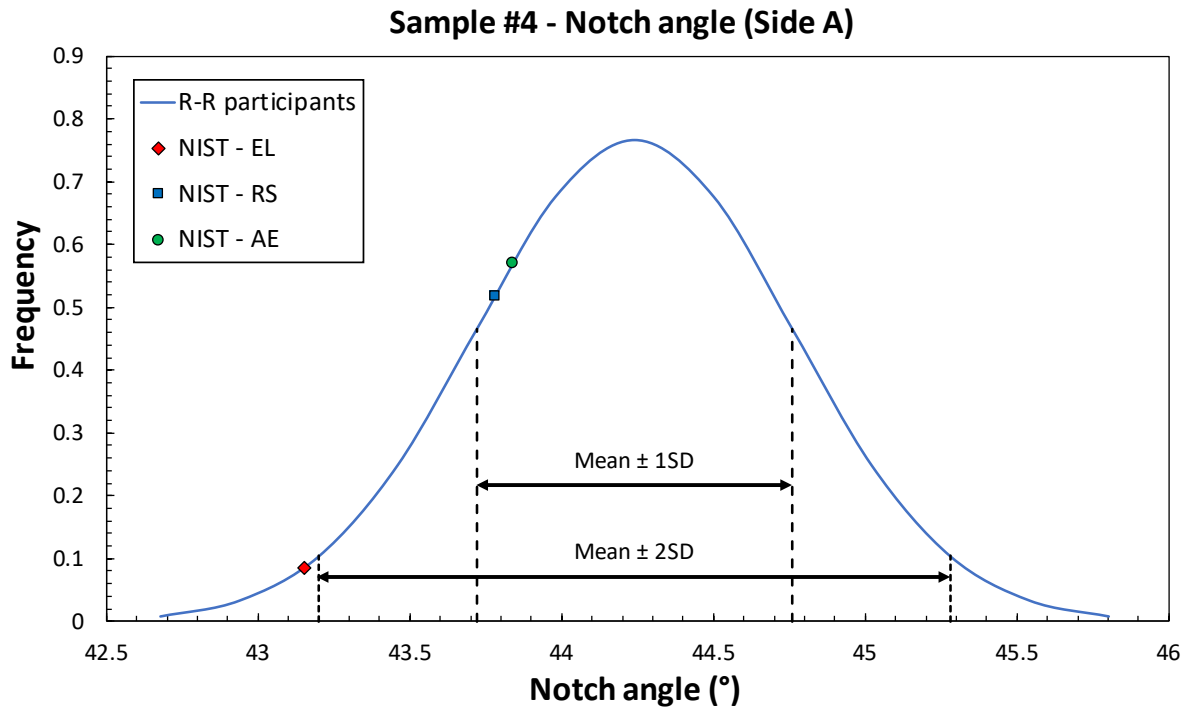

Sample #1 - Notch angle (Side C)
R-R participants
NIST - EL
NIST - RS
NIST - AE
Mean ± 1SD
Mean ± 2SD
Frequency
Notch angle (°)
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
45
45.5
46
46.5
47
47.5
48
48.5
49

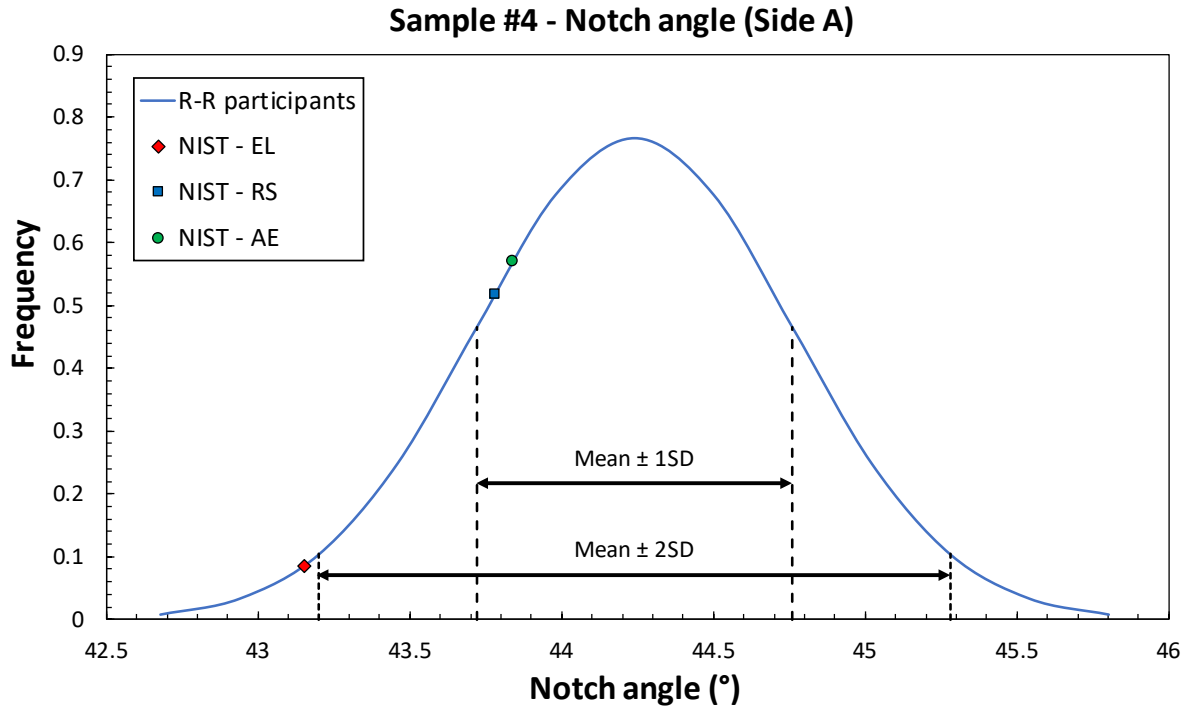

Sample #2 - Notch angle (Side A)
R-R participants
NIST - EL
NIST - RS
NIST - AE
Mean ± 1SD
Mean ± 2SD
Frequency
Notch angle (°)
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
44
44.5
45
45.5
46
46.5
47

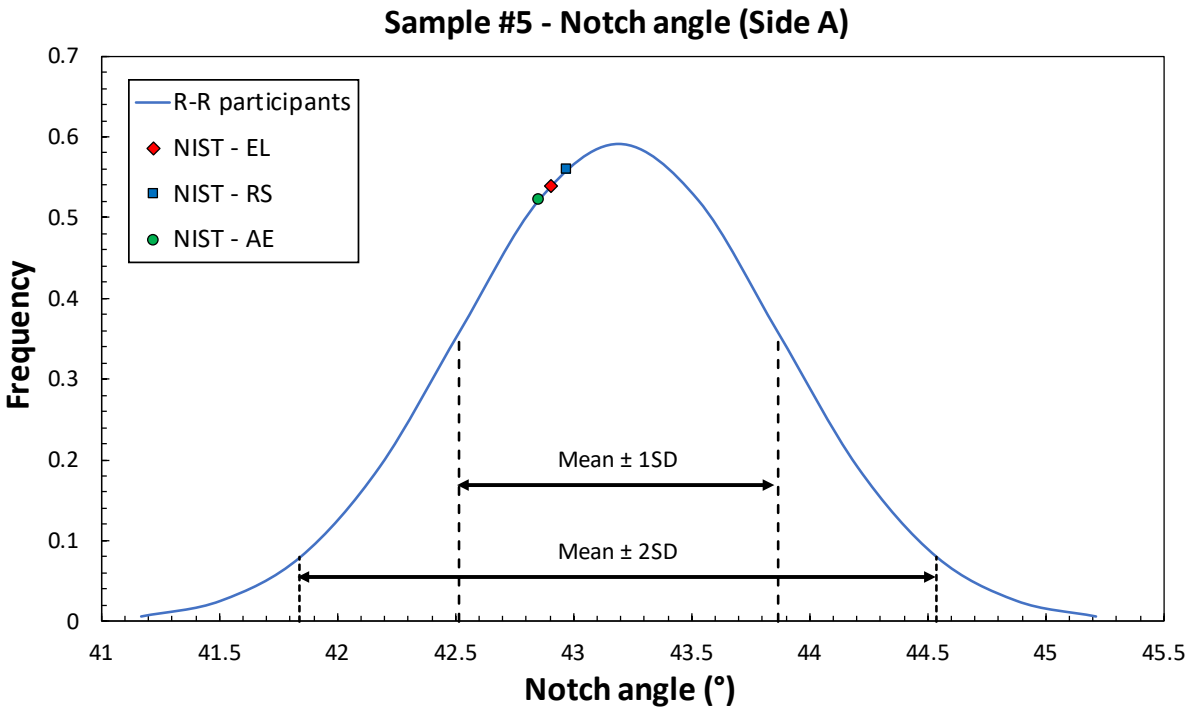

Sample #2 - Notch angle (Side C)
R-R participants
NIST - EL
NIST - RS
NIST - AE
Mean ± 1SD
Mean ± 2SD
Frequency
Notch angle (°)
0
0.2
0.4
0.6
0.8
1
1.2
44
44.5
45
45.5
46
46.5
47

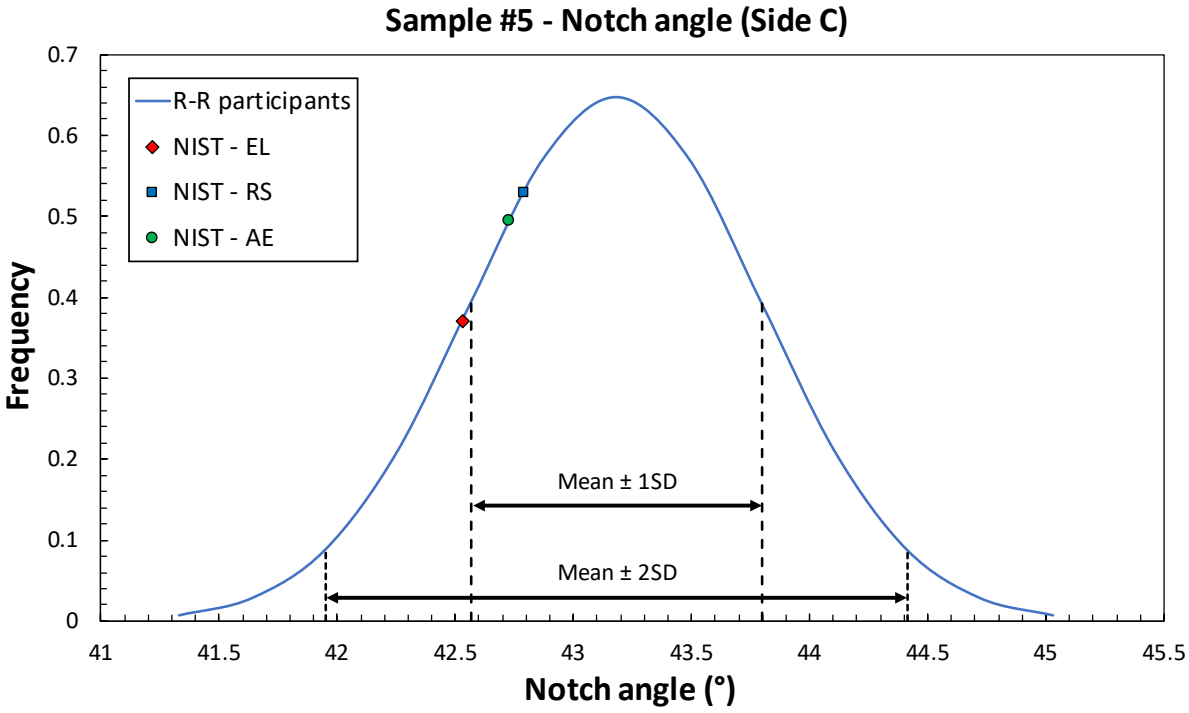

Sample #3 - Notch angle (Side A)
R-R participants
NIST - EL
NIST - RS
NIST - AE
Mean ± 1SD
Mean ± 2SD
Frequency
Notch angle (°)
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
43
43.5
44
44.5
45
45.5
46
46.5
47
47.5
48

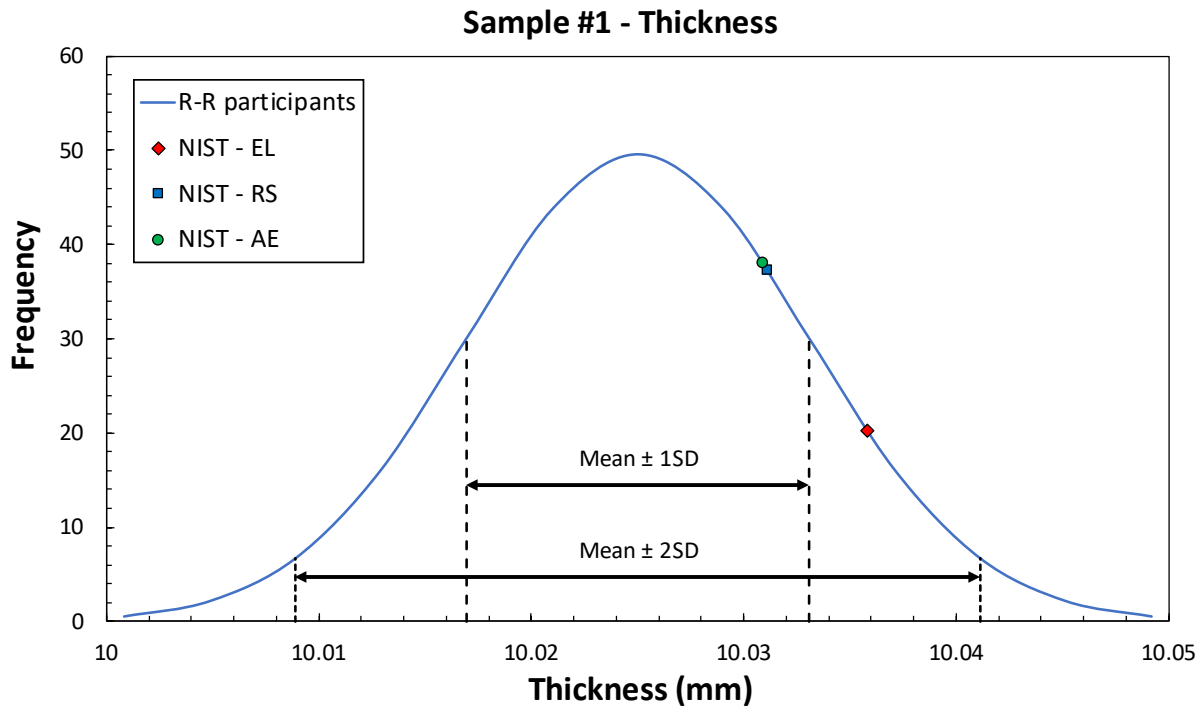

Sample #3 - Notch angle (Side C)
R-R participants
NIST -EL
NIST - RS
NIST - AE
Mean ± 1SD
Mean ± 2SD
Frequency
Notch angle (°)
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
43
43.5
44
44.5
45
45.5
46
46.5
47
47.5
48

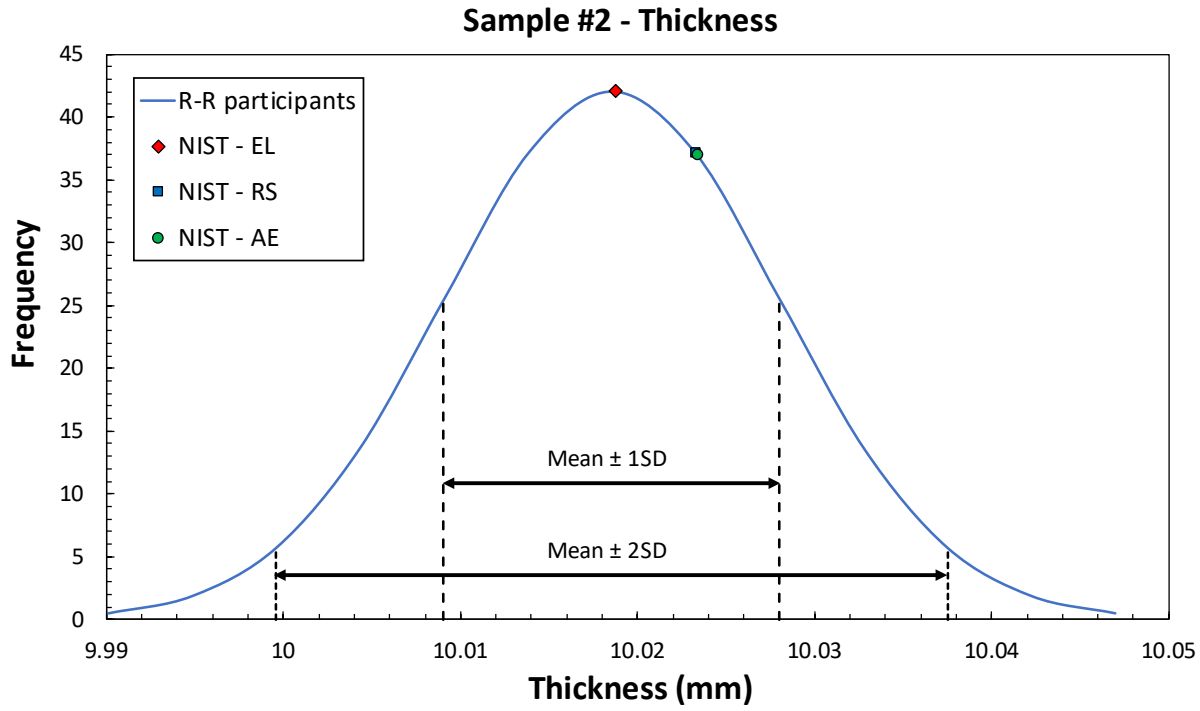

Sample #4 - Notch angle (Side A)
R-R participants
NIST - EL
NIST - RS
NIST - AE
Mean ± 1SD
Mean ± 2SD
Frequency
Notch angle (°)
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
42.5
43
43.5
44
44.5
45
45.5
46

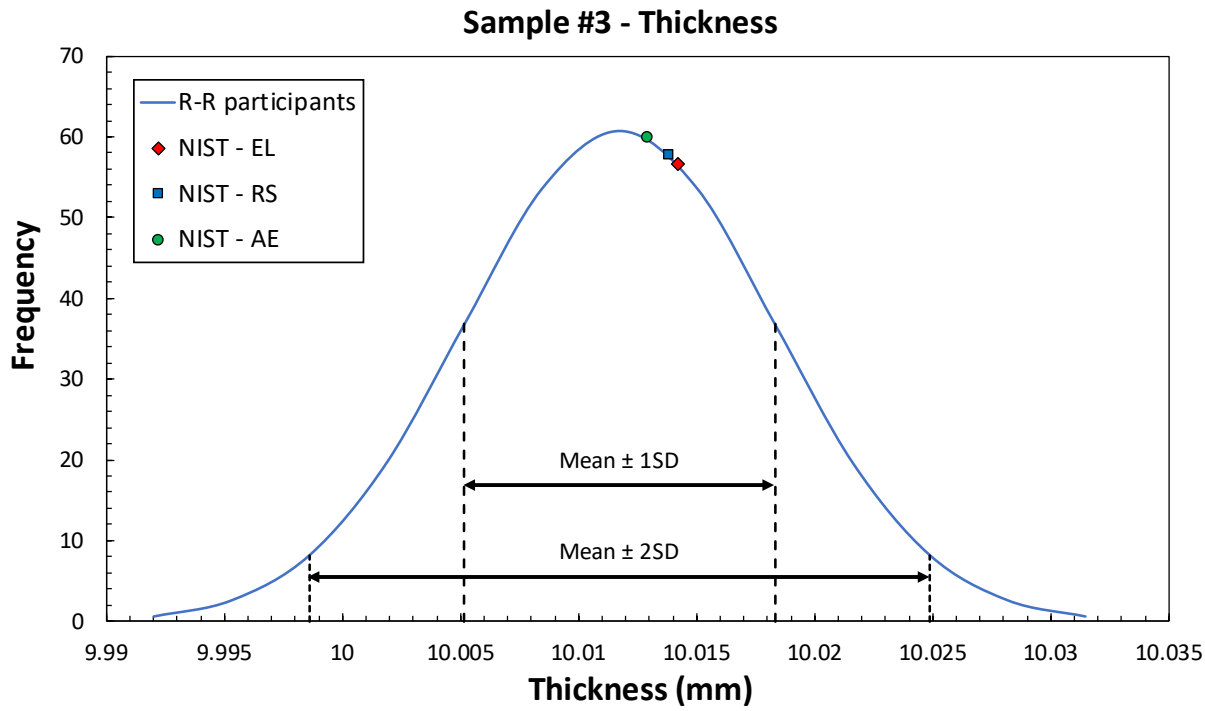

Sample #4 - Notch angle (Side A)
R-R participants
NIST - EL
NIST - RS
NIST - AE
Mean ± 1SD
Mean ± 2SD
Frequency
Notch angle (°)
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
42.5
43
43.5
44
44.5
45
45.5
46

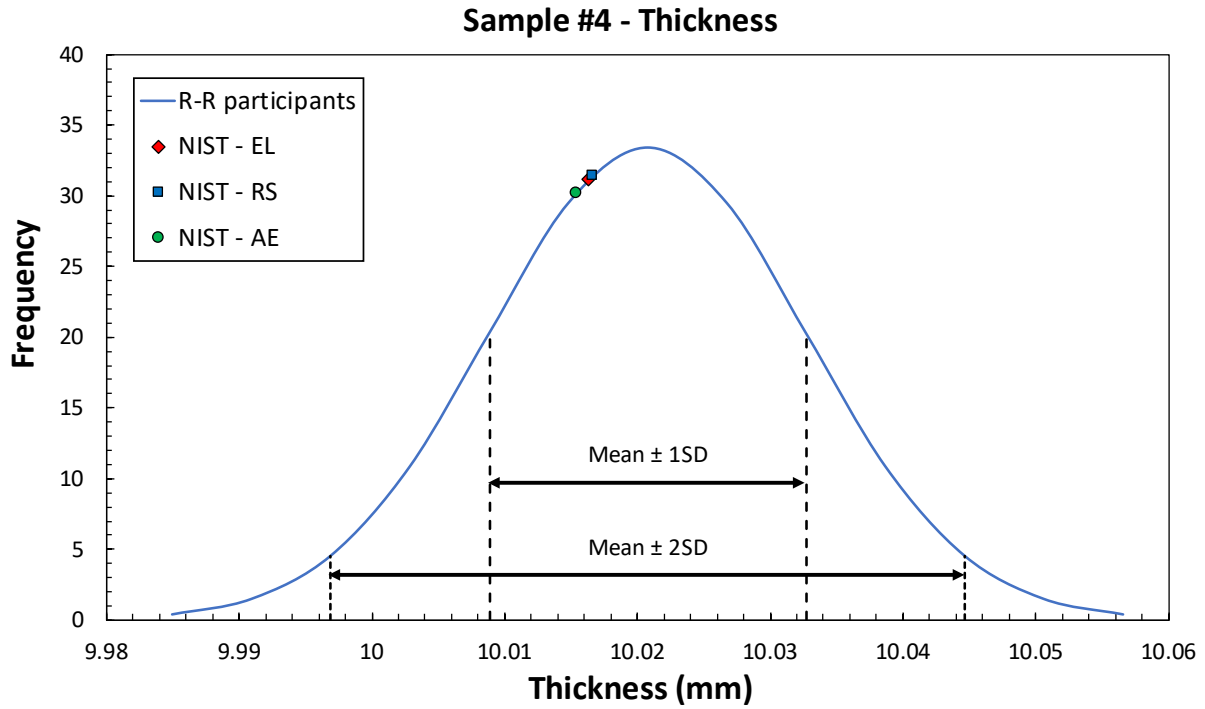

Sample #5 - Notch angle (Side A)
R-R participants
NIST - EL
NIST - RS
NIST - AE
Mean ± 1SD
Mean ± 2SD
Frequency
Notch angle (°)
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
41
41.5
42
42.5
43
43.5
44
44.5
45
45.5

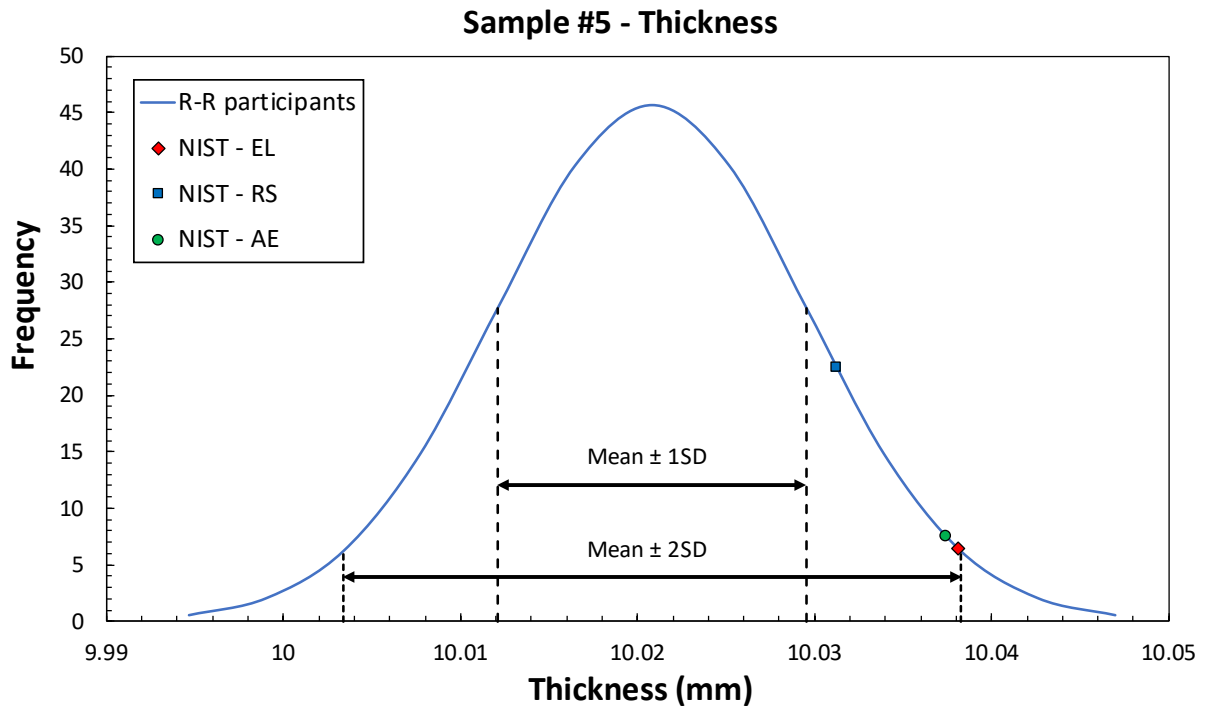

Sample #5 - Notch angle (Side C)
R-R participants
NIST - EL
NIST - RS
NIST - AE
Mean ± 1SD
Mean ± 2SD
Frequency
Notch angle (°)
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
41
41.5
42
42.5
43
43.5
44
44.5
45
45.5

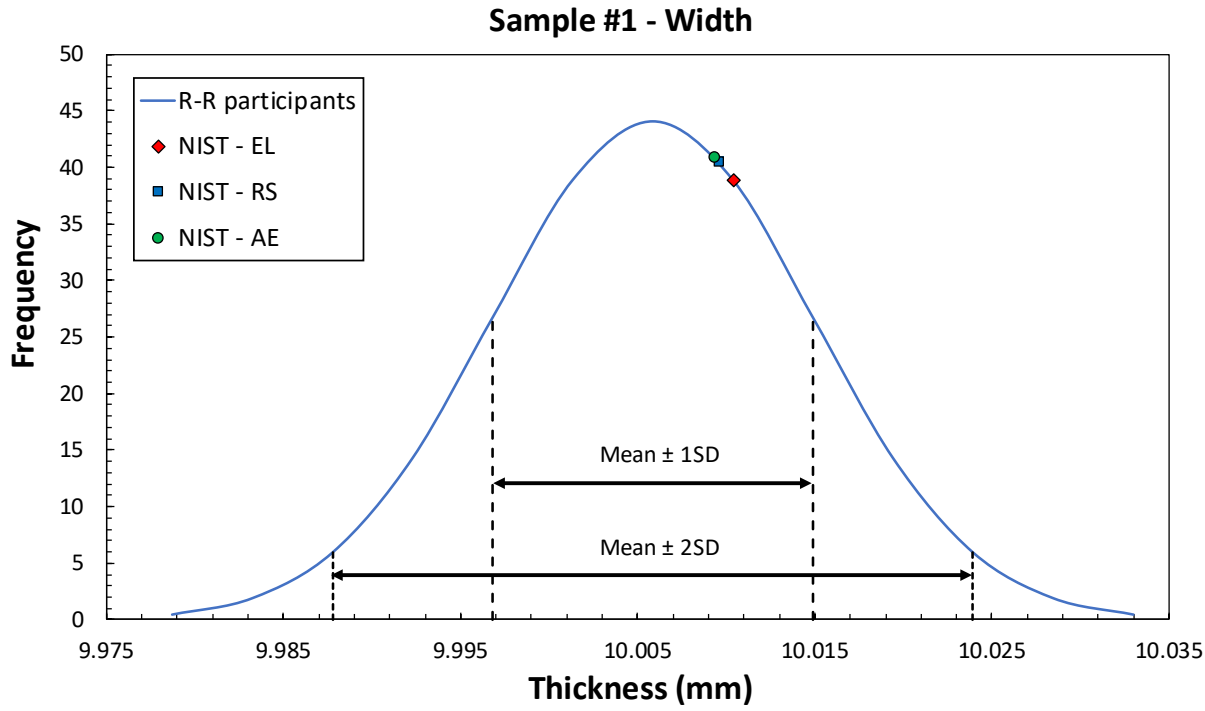

Sample #1 - Thickness
R-R participants
NIST - EL
NIST - RS
NIST - AE
Mean ± 1SD
Mean ± 2SD
Frequency
Thickness (mm)
0
10
20
30
40
50
60
10
10.01
10.02
10.03
10.04
10.05

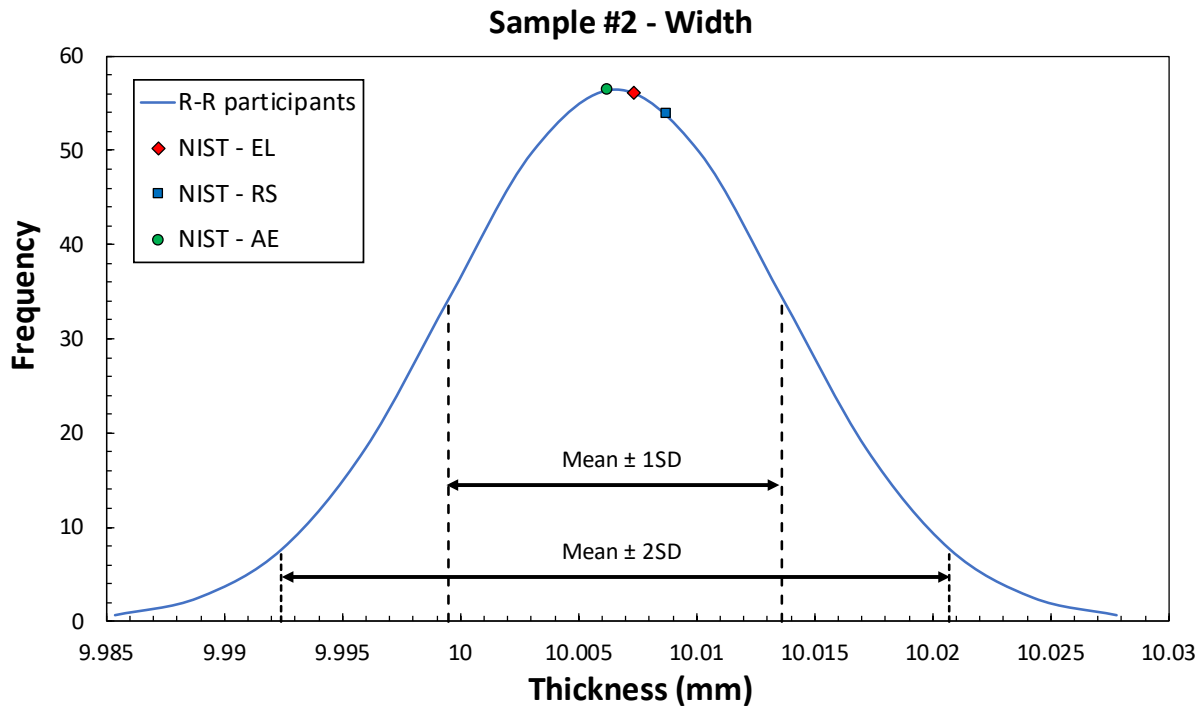

Sample #2 - Thickness
R-R participants
NIST - EL
NIST - RS
NIST - AE
Mean ± 1SD
Mean ± 2SD
Frequency
Thickness (mm)
0
5
10
15
20
25
30
35
40
45
9.99
10
10.01
10.02
10.03
10.04
10.05

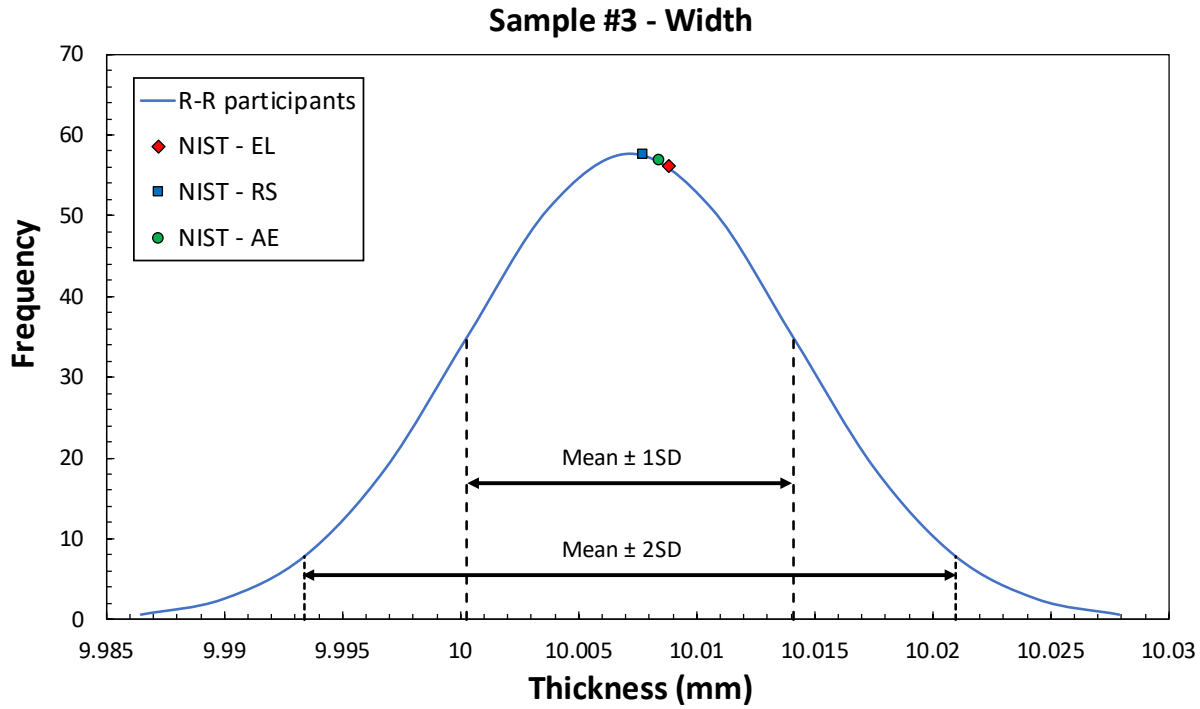

Sample #3 - Thickness
R-R participants
NIST - EL
NIST - RS
NIST - AE
Mean ± 1SD
Mean ± 2SD
Frequency
Thickness (mm)
0
10
20
30
40
50
60
70
9.99
9.995
10
10.005
10.01
10.015
10.02
10.025
10.03
10.035

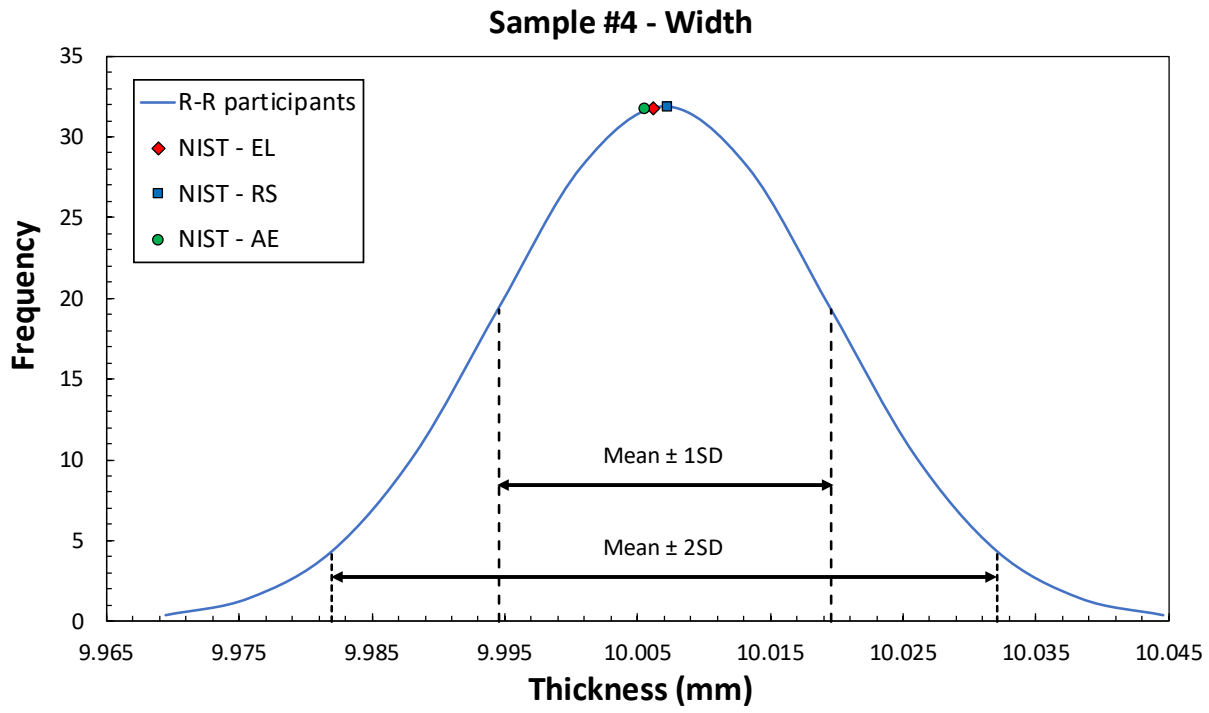

Sample #4 - Thickness
R-R participants
NIST - EL
NIST - RS
NIST - AE
Mean ± 1SD
Mean ± 2SD
Frequency
Thickness (mm)
0
5
10
15
20
25
30
35
40
9.98
9.99
10
10.01
10.02
10.03
10.04
10.05
10.06

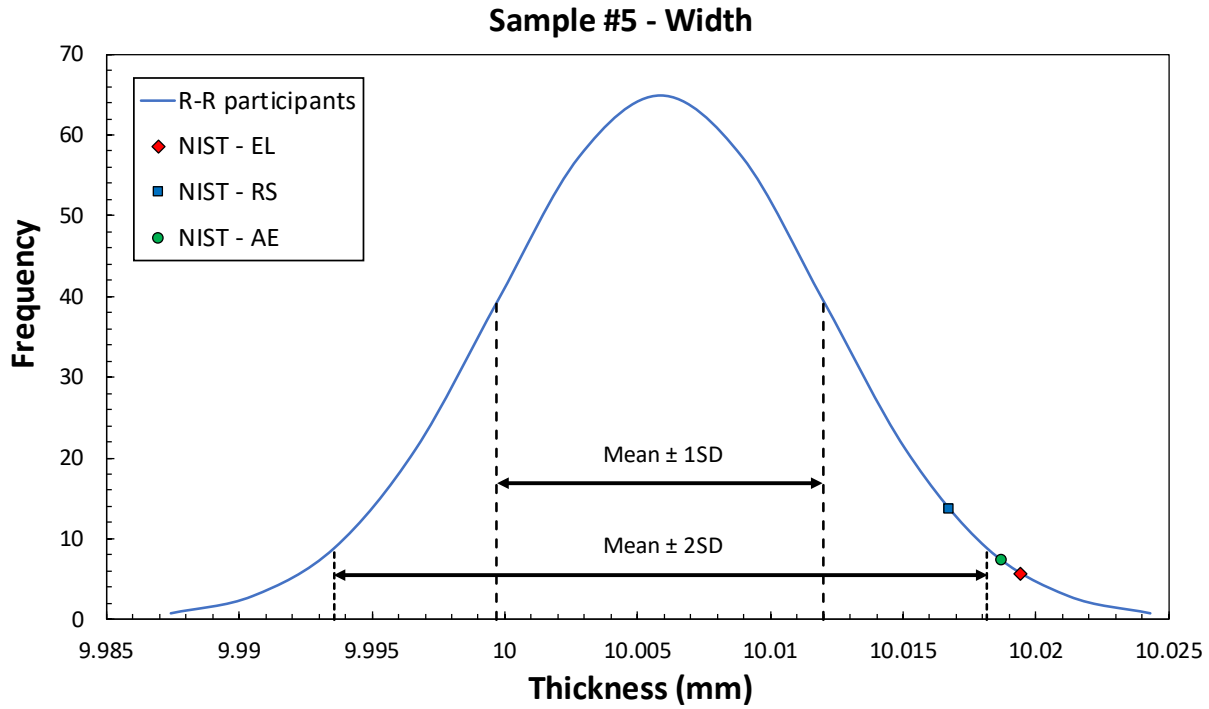

Sample #5 - Thickness
R-R participants
NIST - EL
NIST - RS
NIST - AE
Mean ± 1SD
Mean ± 2SD
Frequency
Thickness (mm)
0
5
10
15
20
25
30
35
40
45
50
9.99
10
10.01
10.02
10.03
10.04
10.05


Sample #1 - Width
R-R participants
NIST - EL
NIST - RS
NIST - AE
Mean ± 1SD
Mean ± 2SD
Frequency
Thickness (mm)
0
5
10
15
20
25
30
35
40
45
50
9.975
9.985
9.995
10.005
10.015
10.025
10.035


Sample #2 - Width
R-R participants
NIST - EL
NIST - RS
NIST - AE
Mean ± 1SD
Mean ± 2SD
Frequency
Thickness (mm)
0
10
20
30
40
50
60
9.985
9.99
9.995
10
10.005
10.01
10.015
10.02
10.025
10.03


Sample #3 - Width
R-R participants
NIST - EL
NIST - RS
NIST - AE
Mean ± 1SD
Mean ± 2SD
Frequency
Thickness (mm)
0
10
20
30
40
50
60
70
9.985
9.99
9.995
10
10.005
10.01
10.015
10.02
10.025
10.03


Sample #4 - Width
R-R participants
NIST - EL
NIST - RS
NIST - AE
Mean ± 1SD
Mean ± 2SD
Frequency
Thickness (mm)
0
5
10
15
20
25
30
35
9.965
9.975
9.985
9.995
10.005
10.015
10.025
10.035
10.045


Sample #5 - Width
R-R participants
NIST - EL
NIST - RS
NIST - AE
Mean ± 1SD
Mean ± 2SD
Frequency
Thickness (mm)
0
10
20
30
40
50
60
70
9.985
9.99
9.995
10
10.005
10.01
10.015
10.02
10.025