Research Report, Committee E-28 on Mechanical Testing

RR: E-28 X XXX **Date: April 11, 2003**

Title: Round Robin Results of Interlaboratory Automated Ball Indentation (ABI) Tests by Task Group E 28.06.14 (ABI Test Methods), Fahmy M. Haggag, Chairman

Draft 7 of the proposed ASTM "***Standard Test Methods for Automated Ball Indentation Testing of Metallic Samples and Structures to Determine Stress-Strain Curves and Ductility at Various Test Temperatures***," (Designation E XXXX) (Z9896Z), that was used for conducting the ABI round robin study is included at the end of this Research Report.

Round Robin Results of Interlaboratory Automated Ball Indentation (ABI) Tests

by Task Group E 28.06.14 (ABI Test Methods), Fahmy M. Haggag, Chairman

Introduction

In order to provide data on which to base the precision statements for the proposed Automated Ball Indentation (ABI) Test Methods of metallic materials (Z9896Z), Task Group E28.06.14 on ABI Test Methods conducted an interlaboratory study (ILS) according to the ASTM Standard Practice E 691-99. The ABI test results and their statistical analyses are presented in this research report.

Test Method

Draft 6 "***Standard Test Methods for Automated Ball Indentation Testing of Metallic Samples and Structures to Determine Stress-Strain Curves and Ductility at Various Test Temperatures***," was used for conducting this round robin study. This draft was balloted in December 2002 by Subcommittee E28.06 and no comments were received regarding the ABI test procedure or the data analysis. A few voters requested the inclusion of the precision values that are the subject of this report. Draft 7 (included at the end of this research report) now includes the precision values determined from this ILS of the ABI Test Methods as well as a few editorial changes (e.g., changing "load" to "force", etc.).

Five ABI tests were conducted on each of four widely differing ferrous and non-ferrous materials at each of six laboratories. The materials are two aluminum alloys (6061 and 7075) and two steel alloys (1018 and 4142) with a wide range of flow properties. This report presents the test results and the statistical analyses made according to ASTM E691-99 "*Standard Practice for Conducting an Interlaboratory Study to Determine the Precision of a Test Method*," using the ASTM Software E691, Windows 2.0.

Participants

The laboratories that participated in this ILS test program for the ABI Test Methods are listed below.

Laboratory	Address	Contact Name
BWXT-Y12, LLC (National Security Complex)	P.O. Box 2009 Bear Creek Road Oak Ridge, TN 37831	Mr. Robert Bridges bridgesrl@y12.doe.gov
Oak Ridge National Laboratory	P.O. Box 2008 Bethel Valley Road Oak Ridge, TN 37831	Mr. Larry Phillips phillipsld@ornl.gov
The University of Tennessee, Knoxville	310 Perkins Hall Knoxville, TN 37996-2030	Dr. John Landes John-Landes@utk.edu
Accurate Machining and Design	251 Midway Lane Oak Ridge, TN 37830	Mr. Sam McLane accurate_machine@bellsouth.net
KISTEK	10320 Daymark Lane Knoxville, TN 37922	Dr. Roberto Lenarduzzi Roberto@kistek.com
Advanced Technology Corporation	1066 Commerce Park Drive Oak Ridge, TN 37830	Mr. Fahmy Haggag Fahmy.Haggag@atc-ssm.com

Interlaboratory Test Program Instructions

The following instructions and test procedure were sent as an e-mail message to all participants.

For this ILS (round robin) work we have selected two steels (1018 and 4142) and two aluminum (6061 and 7075) materials with different strength levels for each material type (ferrous and non-ferrous). The steel and aluminum samples are defined as S1X, S2X, A1X, and A2X, respectively (where X defines the sample number). The specimens are appropriately machined and polished, and ready for ABI testing. Please perform the testing on each material in the same day. The estimated time for all 20 ABI tests (five tests per sample) is approximately two (2) hours. The ASTM Draft No. 7 of the ABI Test Methods is attached for use in this ILS work. I have purchased the ASTM software of the ILS statistical analysis per ASTM Practice E 691. This software will be used to generate the repeatability and reproducibility statement for the following parameters: Yield Strength, Estimated UTS, strain-hardening exponent, and strength coefficient. The precision statement is mandatory for all ASTM standard test methods.

Please perform five (5) ABI tests on each sample. A suggested test name could be: Organization Initials-Sample Number-Test Number (e.g., UCSD-SXX-X). A brazed 0.062-inch (1.57-mm) diameter tungsten carbide indenter shall be used in all 20 ABI tests. In order to incorporate the Precision Values in the ASTM Standard ABI Test Methods before the May 2003 meeting, I need to receive the tabulated summary test results (*.txt) in both English and SI units as well as the complete electronic files (*.bin, *.hdr, and *.ana) either by e-mail or on a CD by April 11, 2003. The centerline of all ABI tests should be spaced at 0.20 inch or greater. A summary of the ABI test and analysis parameters is included below.

Test Parameters:

Indenter speed = 0.0006 in/s
Percentage indenter used = 20%
Pre-Load Set Point = 15 lb
Number of Unloading Cycles = 10 (Equal Depth)
Unload (% of Cycle Max. Load) = 40.0
Data Acquisition Rate = 200 samples/sec
Indenter Elastic Modulus = 93,000,000 psi

Analysis Parameters for Steel Samples:

Elastic Modulus = 30,000,000 psi
Constraint Factor (Alpha) = 1.00
Yield Strength Slope (Beta) = 0.2600
Include Yield Parameter in Analysis = Yes

Analysis Parameters for Aluminum Samples:

Elastic Modulus = 10,000,000 psi
Constraint Factor (Alpha) = 1.00
Yield Strength Slope (Beta) = 0.3100
Include Yield Parameter in Analysis = Yes

If you have any question please contact me. Thank you for participation in this cooperative ILS.

Best regards,

Fahmy M. Haggag
Chairman, ASTM E28.06.14 Task Group on ABI Test Methods

Results and Statistical Data Summary

The five ABI test results of yield strength (YS-ABI), estimated ultimate strength (UTS-ABI), strength coefficient (K-ABI), strain-hardening exponent (n-ABI), and calculated uniform ductility (UD-ABI) received from all laboratories for each of the four metallic materials are shown in Table 1 (A through E). These ABI test results were received in an electronic table format (*.txt). The test name and material were defined as per the instructions' e-mail message to all participants (described in the previous section). All test results were analyzed using the ASTM software E691, Window 2.0, and the test data and results are provided as screen captures from the software. Furthermore, all the test data and their standard deviations (the latter is calculated using the Microsoft Excel® spreadsheet program) are provided in Appendix A in both SI and English units. The standard deviations from both the ASTM E691 software and the Excel spread sheet program are in excellent agreement, indicating that all test data from the six laboratories were entered (although manually) correctly into the ASTM E691 software.

Table 2 (A through E) presents the Precision Statements for the five ABI Properties/Determinations (YS-ABI, UTS-ABI, K-ABI, n-ABI, and UD-ABI) for the four materials. The standard deviations within labs and between laboratories (Sr, and SR) were also calculated using the Excel spread sheet and the results are in very good agreement with those calculated using the ASTM E691 software as shown in Table A1 of Appendix A (in SI units). Table A2 of this Appendix shows the same data in English units. Table 3 (A through E) presents the same precision summary of Table 2 with the addition of the repeatability coefficient of variation in percent both within a laboratory and between laboratories.

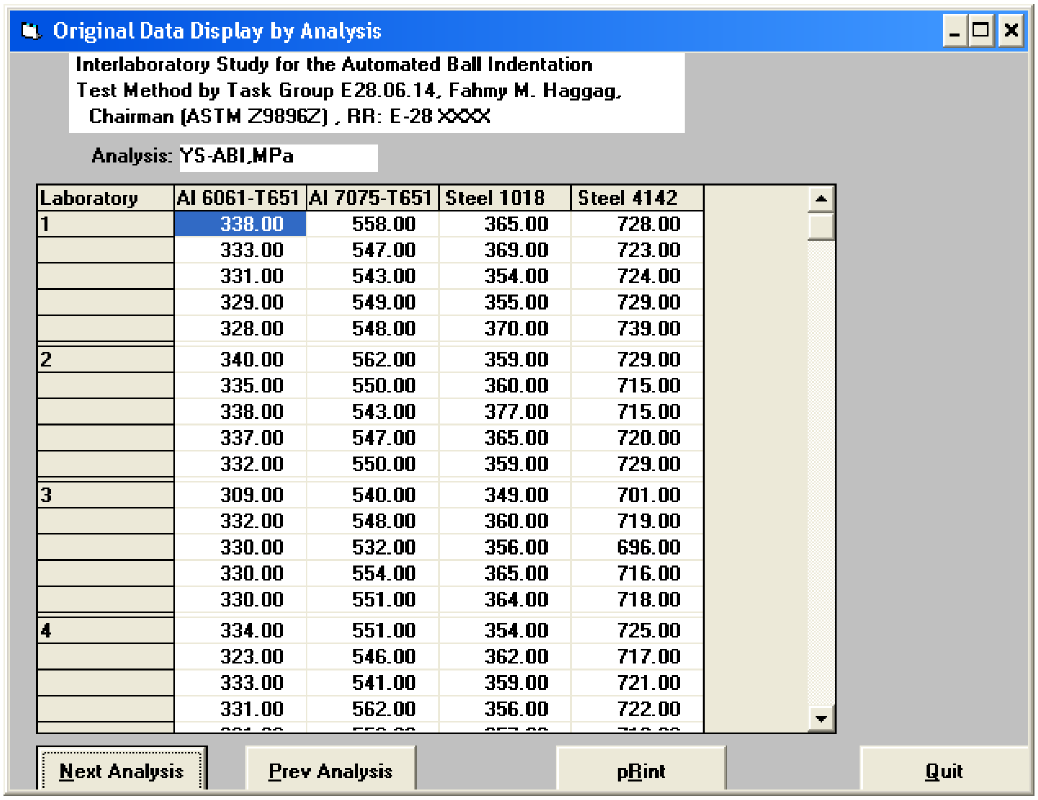
The calculation worksheets of the five ABI properties/determinations are shown in Table 4 (A through E) for the individual laboratories by material. The consistency statistics, "h" and "k" (Section 15 of the ASTM Standard Practice E691-99) values are shown in Tables 5 and 6 for the five ABI properties (YS-ABI, UTS-ABI, K-ABI, n-ABI, and UD-ABI).

Figure 1 is a plot of the repeatability and reproducibility (r and R) by the five ABI-determined properties. Figures 2 and 3 are plots of the consistency statistic values (h, k) for the five ABI-determined properties by laboratory and by materials, respectively. Figure 4 presents five plots of the individual and average material values of the five ABI property determinations.

Research Report Summary

The ABI test results from five tests each on four materials (ferrous and non-ferrous) at six laboratories demonstrate that the ABI Test Methods provide excellent repeatability within a laboratory and between laboratories for the ABI-determined yield strength (YS-ABI), estimated ultimate strength (UTS-ABI), and the strength coefficient (K-ABI). The repeatability coefficients of variation for the strain-hardening exponent (n-ABI) and the uniform ductility (UD-ABI) are slightly higher because the determination of these properties depends on the shape (curvature) of the true-stress/true-plastic-strain curve and the homogeneity of the metal. The precision values for five ABI properties/determinations are presented as screen capture tables from the ASTM E691 software in Table 2. Table 3 (A through E) presents the same precision summary of Table 2 with the addition of determining the repeatability coefficient of variation in percent within a laboratory and between laboratories. The additional CV $\%_r$ and CV $\%_R$ analyses of Table 3 are added for convenience to allow any user of the ABI Test Methods to compare their precision statements to some of those listed in the Precision Statement (Section 9.1) of the ASTM E 8-00 "Standard Test Methods for Tension Testing of Metallic materials."

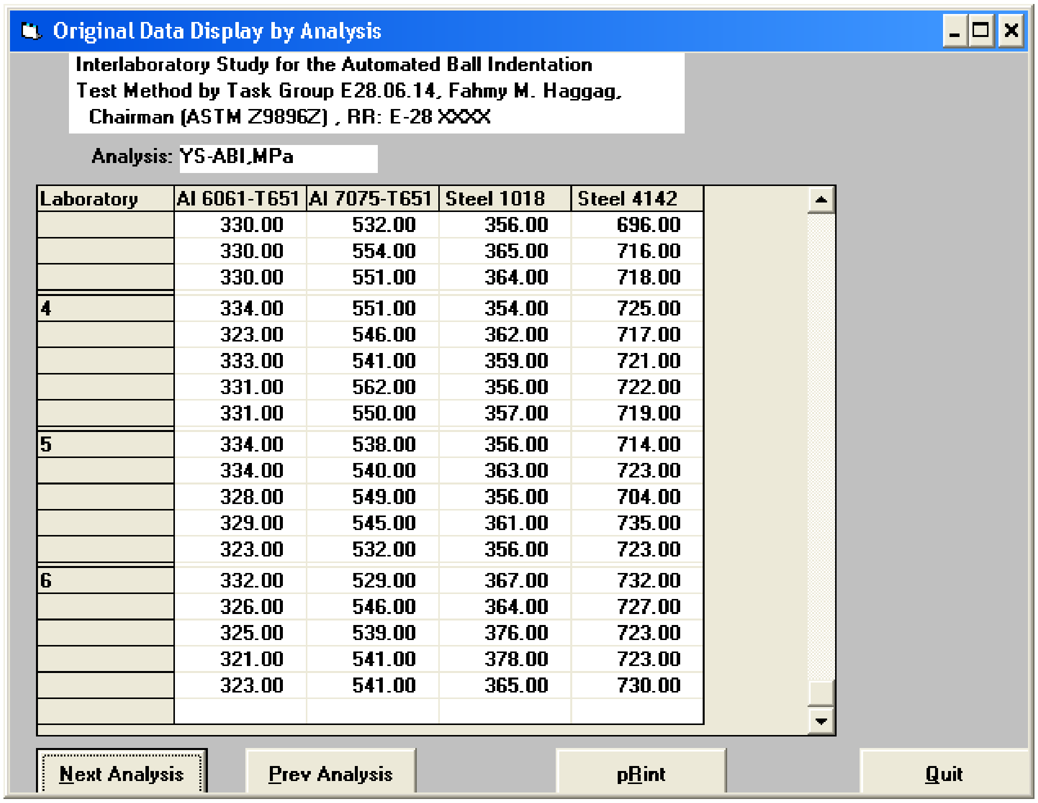
Table 1A - Yield Strength (YS-ABI) from Individual ABI Tests, MPa



Interlaboratory Study for the Automated Ball Indentation
Test Method by Task Group E28.06.14, Fahmy M. Haggag,
Chairman (ASTM Z9896Z) , RR: E-28 XXXX

Analysis: YS-ABI,MPa

Laboratory	Al 6061-T651	Al 7075-T651	Steel 1018	Steel 4142
1	338.00	558.00	365.00	728.00
	333.00	547.00	369.00	723.00
	331.00	543.00	354.00	724.00
	329.00	549.00	355.00	729.00
	328.00	548.00	370.00	739.00
2	340.00	562.00	359.00	729.00
	335.00	550.00	360.00	715.00
	338.00	543.00	377.00	715.00
	337.00	547.00	365.00	720.00
	332.00	550.00	359.00	729.00
3	309.00	540.00	349.00	701.00
	332.00	548.00	360.00	719.00
	330.00	532.00	356.00	696.00
	330.00	554.00	365.00	716.00
	330.00	551.00	364.00	718.00
4	334.00	551.00	354.00	725.00
	323.00	546.00	362.00	717.00
	333.00	541.00	359.00	721.00
	331.00	562.00	356.00	722.00

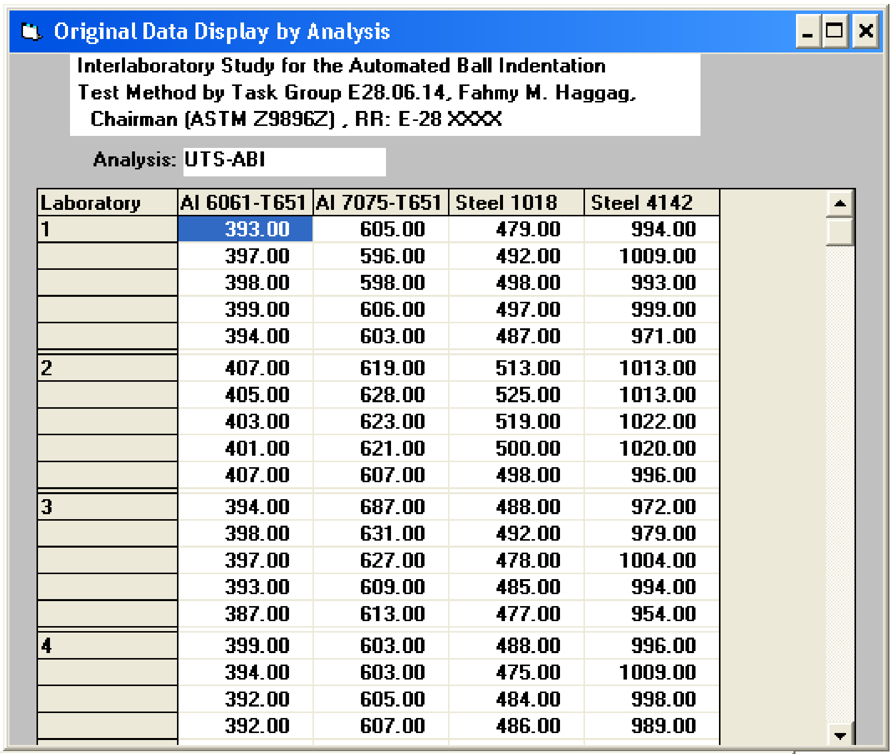


Interlaboratory Study for the Automated Ball Indentation
Test Method by Task Group E28.06.14, Fahmy M. Haggag,
Chairman (ASTM Z9896Z) , RR: E-28 XXXX

Analysis: YS-ABI,MPa

Laboratory	Al 6061-T651	Al 7075-T651	Steel 1018	Steel 4142
	330.00	532.00	356.00	696.00
	330.00	554.00	365.00	716.00
	330.00	551.00	364.00	718.00
4	334.00	551.00	354.00	725.00
	323.00	546.00	362.00	717.00
	333.00	541.00	359.00	721.00
	331.00	562.00	356.00	722.00
	331.00	550.00	357.00	719.00
5	334.00	538.00	356.00	714.00
	334.00	540.00	363.00	723.00
	328.00	549.00	356.00	704.00
	329.00	545.00	361.00	735.00
	323.00	532.00	356.00	723.00
6	332.00	529.00	367.00	732.00
	326.00	546.00	364.00	727.00
	325.00	539.00	376.00	723.00
	321.00	541.00	378.00	723.00
	323.00	541.00	365.00	730.00

Table 1B - Estimated Ultimate Strength (UTS-ABI) from Individual ABI Tests, MPa

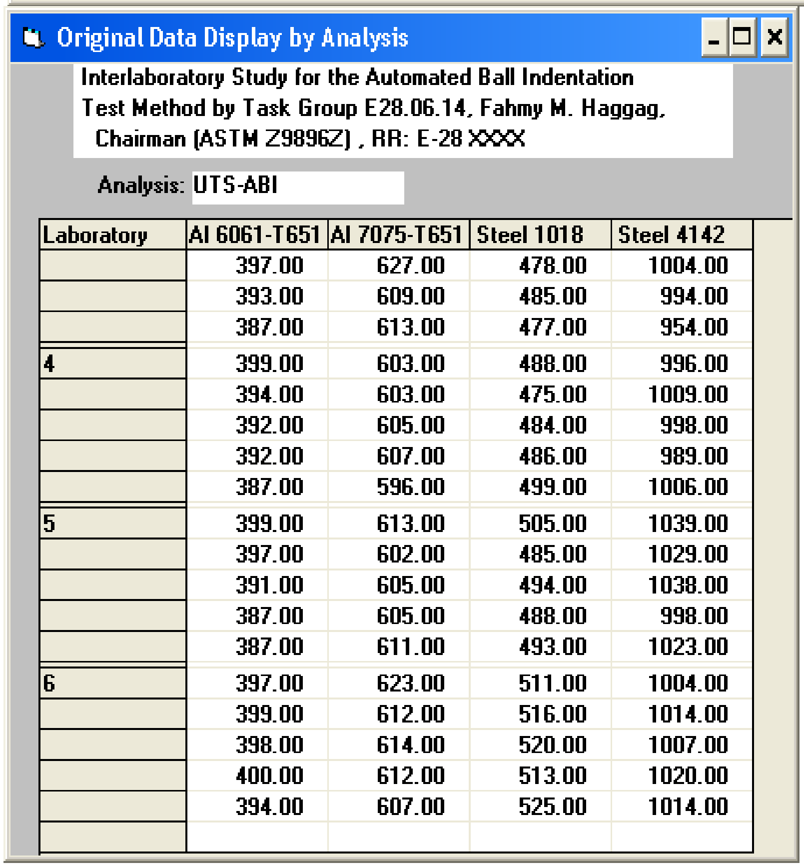


Original Data Display by Analysis

Interlaboratory Study for the Automated Ball Indentation
Test Method by Task Group E28.06.14, Fahmy M. Haggag,
Chairman (ASTM Z9896Z) , RR: E-28 XXXX

Analysis: UTS-ABI

Laboratory	Al 6061-T651	Al 7075-T651	Steel 1018	Steel 4142
1	393.00	605.00	479.00	994.00
	397.00	596.00	492.00	1009.00
	398.00	598.00	498.00	993.00
	399.00	606.00	497.00	999.00
	394.00	603.00	487.00	971.00
2	407.00	619.00	513.00	1013.00
	405.00	628.00	525.00	1013.00
	403.00	623.00	519.00	1022.00
	401.00	621.00	500.00	1020.00
	407.00	607.00	498.00	996.00
3	394.00	687.00	488.00	972.00
	398.00	631.00	492.00	979.00
	397.00	627.00	478.00	1004.00
	393.00	609.00	485.00	994.00
	387.00	613.00	477.00	954.00
4	399.00	603.00	488.00	996.00
	394.00	603.00	475.00	1009.00
	392.00	605.00	484.00	998.00
	392.00	607.00	486.00	989.00



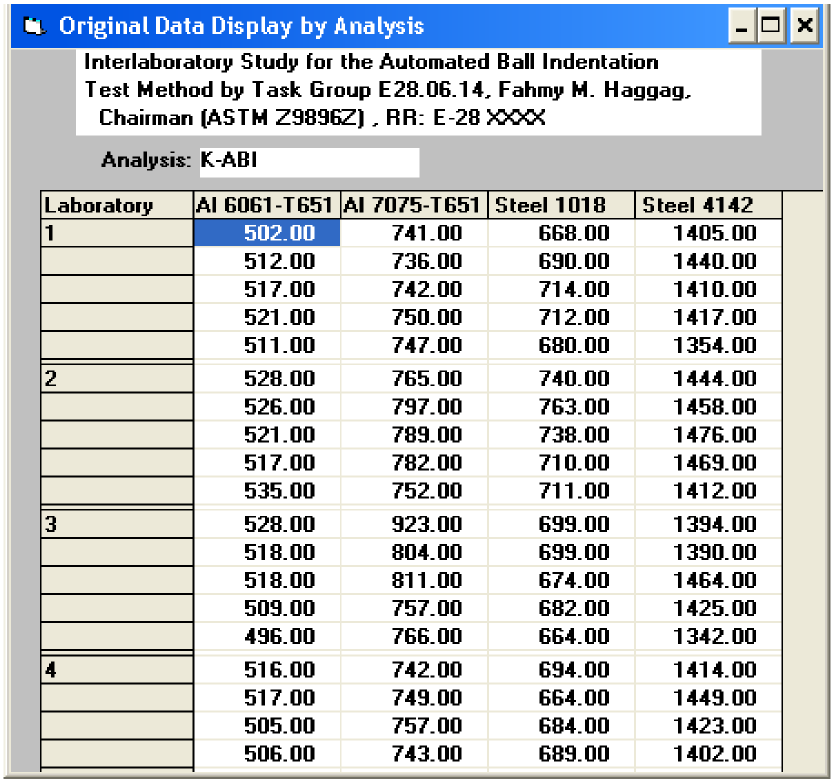
Original Data Display by Analysis

Interlaboratory Study for the Automated Ball Indentation
Test Method by Task Group E28.06.14, Fahmy M. Haggag,
Chairman (ASTM Z9896Z) , RR: E-28 XXXX

Analysis: UTS-ABI

Laboratory	Al 6061-T651	Al 7075-T651	Steel 1018	Steel 4142
	397.00	627.00	478.00	1004.00
	393.00	609.00	485.00	994.00
	387.00	613.00	477.00	954.00
4	399.00	603.00	488.00	996.00
	394.00	603.00	475.00	1009.00
	392.00	605.00	484.00	998.00
	392.00	607.00	486.00	989.00
	387.00	596.00	499.00	1006.00
5	399.00	613.00	505.00	1039.00
	397.00	602.00	485.00	1029.00
	391.00	605.00	494.00	1038.00
	387.00	605.00	488.00	998.00
	387.00	611.00	493.00	1023.00
6	397.00	623.00	511.00	1004.00
	399.00	612.00	516.00	1014.00
	398.00	614.00	520.00	1007.00
	400.00	612.00	513.00	1020.00
	394.00	607.00	525.00	1014.00

Table 1C - Strength Coefficient (K-ABI) from Individual ABI Tests, MPa



Interlaboratory Study for the Automated Ball Indentation
Test Method by Task Group E28.06.14, Fahmy M. Haggag,
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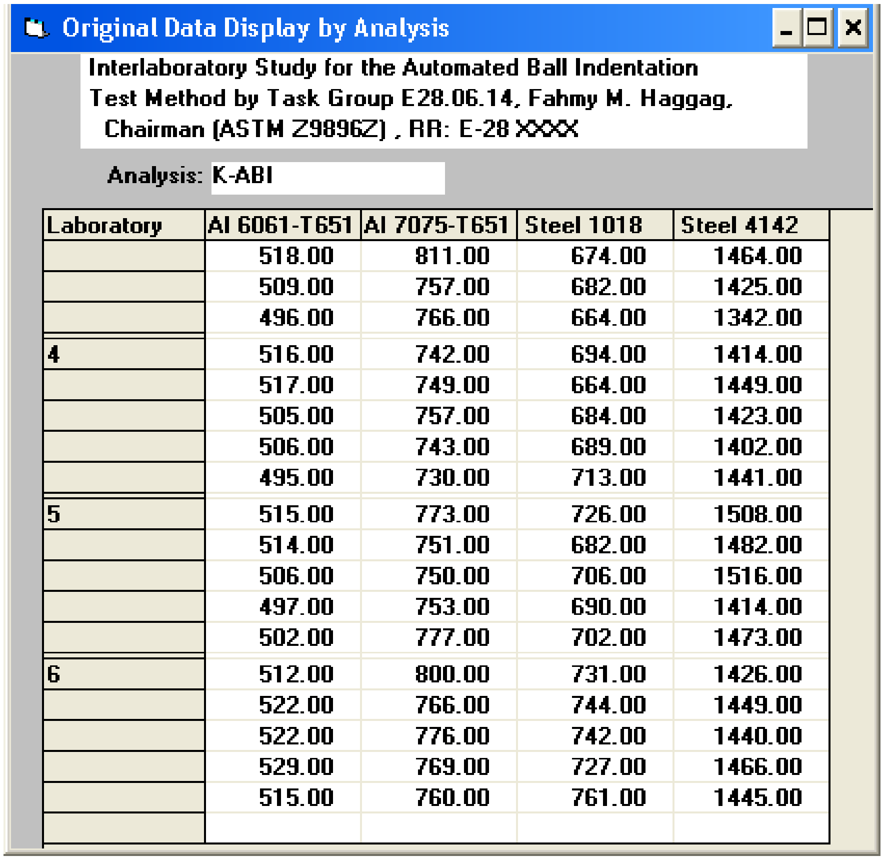
Analysis: K-ABI

Laboratory	Al 6061-T651	Al 7075-T651	Steel 1018	Steel 4142
1	502.00	741.00	668.00	1405.00
	512.00	736.00	690.00	1440.00
	517.00	742.00	714.00	1410.00
	521.00	750.00	712.00	1417.00
	511.00	747.00	680.00	1354.00
2	528.00	765.00	740.00	1444.00
	526.00	797.00	763.00	1458.00
	521.00	789.00	738.00	1476.00
	517.00	782.00	710.00	1469.00
	535.00	752.00	711.00	1412.00
3	528.00	923.00	699.00	1394.00
	518.00	804.00	699.00	1390.00
	518.00	811.00	674.00	1464.00
	509.00	757.00	682.00	1425.00
	496.00	766.00	664.00	1342.00
4	516.00	742.00	694.00	1414.00
	517.00	749.00	664.00	1449.00
	505.00	757.00	684.00	1423.00
	506.00	743.00	689.00	1402.00



Interlaboratory Study for the Automated Ball Indentation
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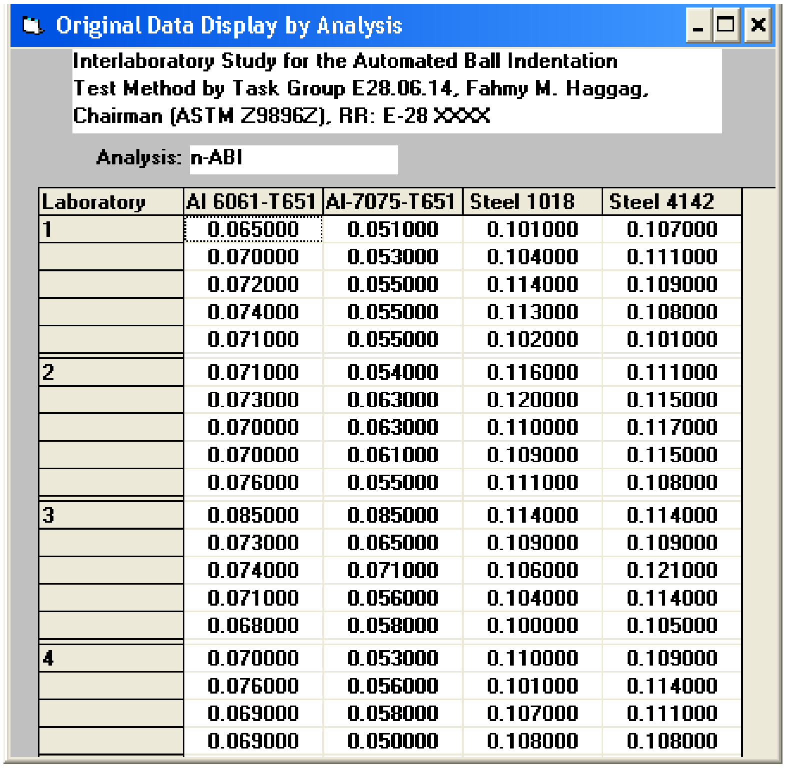
Analysis: K-ABI

Laboratory	Al 6061-T651	Al 7075-T651	Steel 1018	Steel 4142
	518.00	811.00	674.00	1464.00
	509.00	757.00	682.00	1425.00
	496.00	766.00	664.00	1342.00
4	516.00	742.00	694.00	1414.00
	517.00	749.00	664.00	1449.00
	505.00	757.00	684.00	1423.00
	506.00	743.00	689.00	1402.00
	495.00	730.00	713.00	1441.00
5	515.00	773.00	726.00	1508.00
	514.00	751.00	682.00	1482.00
	506.00	750.00	706.00	1516.00
	497.00	753.00	690.00	1414.00
	502.00	777.00	702.00	1473.00
6	512.00	800.00	731.00	1426.00
	522.00	766.00	744.00	1449.00
	522.00	776.00	742.00	1440.00
	529.00	769.00	727.00	1466.00
	515.00	760.00	761.00	1445.00

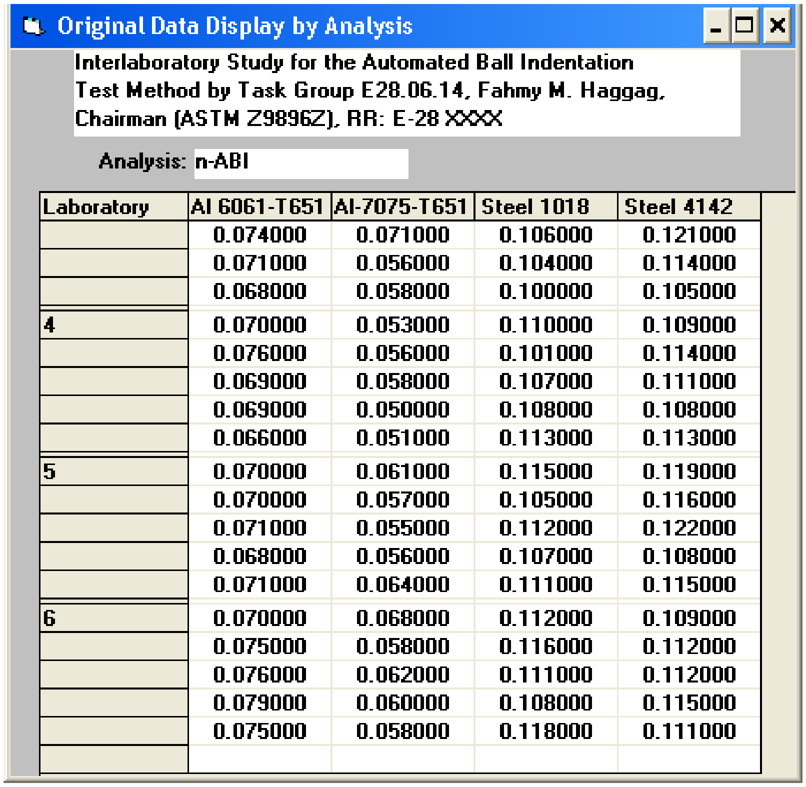
Table 1D – Strain-Hardening Exponent (n-ABI) from Individual ABI Tests



Interlaboratory Study for the Automated Ball Indentation
Test Method by Task Group E28.06.14, Fahmy M. Haggag,
Chairman (ASTM Z9896Z), RR: E-28 XXXX

Analysis: n-ABI

Laboratory	Al 6061-T651	Al-7075-T651	Steel 1018	Steel 4142
1	0.065000	0.051000	0.101000	0.107000
	0.070000	0.053000	0.104000	0.111000
	0.072000	0.055000	0.114000	0.109000
	0.074000	0.055000	0.113000	0.108000
	0.071000	0.055000	0.102000	0.101000
2	0.071000	0.054000	0.116000	0.111000
	0.073000	0.063000	0.120000	0.115000
	0.070000	0.063000	0.110000	0.117000
	0.070000	0.061000	0.109000	0.115000
	0.076000	0.055000	0.111000	0.108000
3	0.085000	0.085000	0.114000	0.114000
	0.073000	0.065000	0.109000	0.109000
	0.074000	0.071000	0.106000	0.121000
	0.071000	0.056000	0.104000	0.114000
	0.068000	0.058000	0.100000	0.105000
4	0.070000	0.053000	0.110000	0.109000
	0.076000	0.056000	0.101000	0.114000
	0.069000	0.058000	0.107000	0.111000
	0.069000	0.050000	0.108000	0.108000

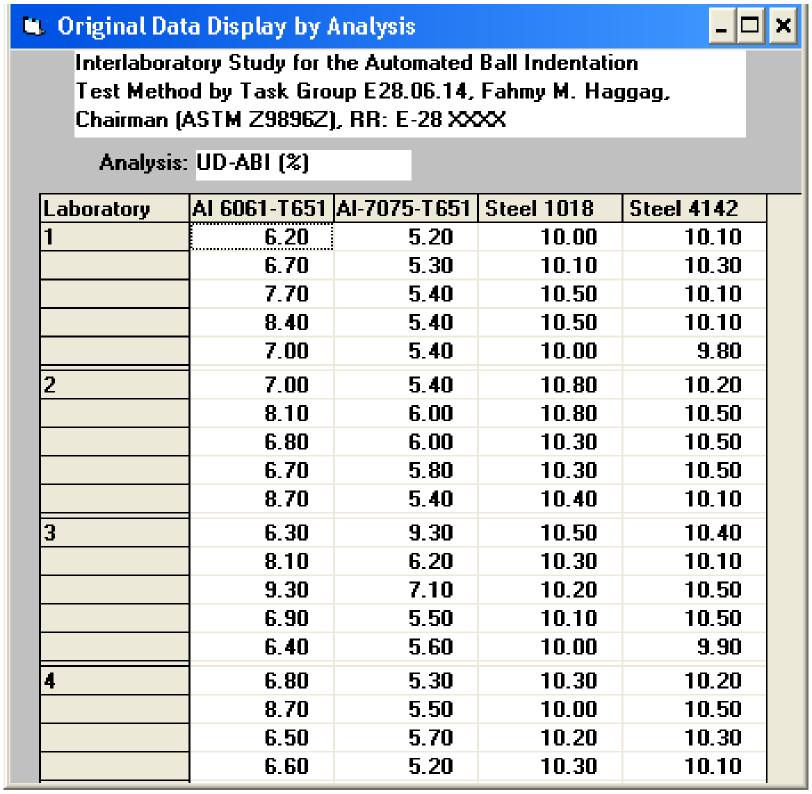


Interlaboratory Study for the Automated Ball Indentation
Test Method by Task Group E28.06.14, Fahmy M. Haggag,
Chairman (ASTM Z9896Z), RR: E-28 XXXX

Analysis: n-ABI

Laboratory	Al 6061-T651	Al-7075-T651	Steel 1018	Steel 4142
	0.074000	0.071000	0.106000	0.121000
	0.071000	0.056000	0.104000	0.114000
	0.068000	0.058000	0.100000	0.105000
4	0.070000	0.053000	0.110000	0.109000
	0.076000	0.056000	0.101000	0.114000
	0.069000	0.058000	0.107000	0.111000
	0.069000	0.050000	0.108000	0.108000
	0.066000	0.051000	0.113000	0.113000
5	0.070000	0.061000	0.115000	0.119000
	0.070000	0.057000	0.105000	0.116000
	0.071000	0.055000	0.112000	0.122000
	0.068000	0.056000	0.107000	0.108000
	0.071000	0.064000	0.111000	0.115000
6	0.070000	0.068000	0.112000	0.109000
	0.075000	0.058000	0.116000	0.112000
	0.076000	0.062000	0.111000	0.112000
	0.079000	0.060000	0.108000	0.115000
	0.075000	0.058000	0.118000	0.111000

Table 1E – Calculated Uniform Ductility (UD-ABI) from Individual ABI Tests, (%)



Interlaboratory Study for the Automated Ball Indentation
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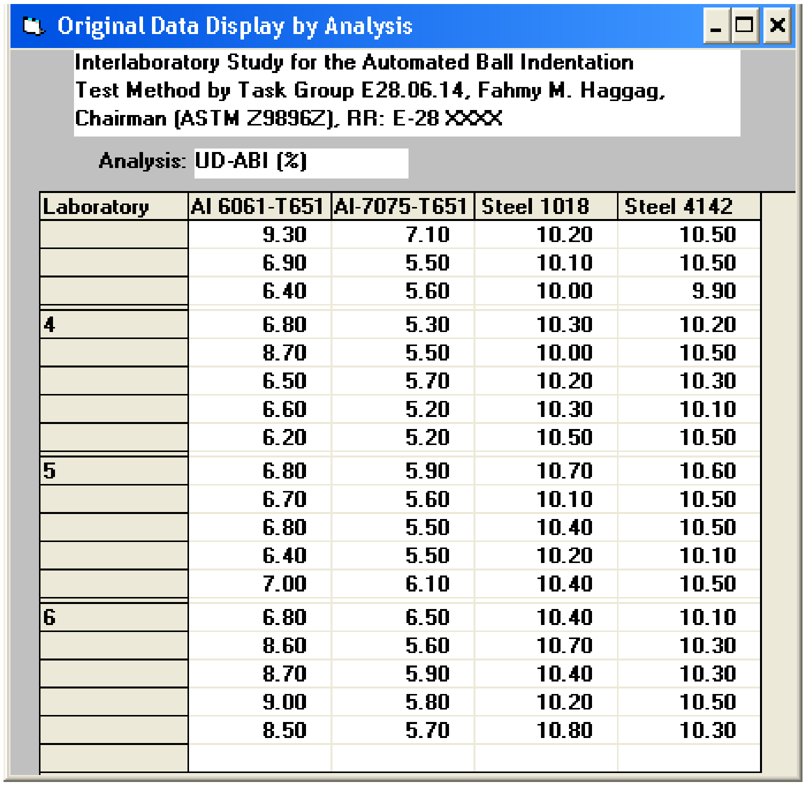
Analysis: UD-ABI (%)

Laboratory	Al 6061-T651	Al-7075-T651	Steel 1018	Steel 4142
1	6.20	5.20	10.00	10.10
	6.70	5.30	10.10	10.30
	7.70	5.40	10.50	10.10
	8.40	5.40	10.50	10.10
	7.00	5.40	10.00	9.80
2	7.00	5.40	10.80	10.20
	8.10	6.00	10.80	10.50
	6.80	6.00	10.30	10.50
	6.70	5.80	10.30	10.50
	8.70	5.40	10.40	10.10
3	6.30	9.30	10.50	10.40
	8.10	6.20	10.30	10.10
	9.30	7.10	10.20	10.50
	6.90	5.50	10.10	10.50
	6.40	5.60	10.00	9.90
4	6.80	5.30	10.30	10.20
	8.70	5.50	10.00	10.50
	6.50	5.70	10.20	10.30
	6.60	5.20	10.30	10.10



Interlaboratory Study for the Automated Ball Indentation
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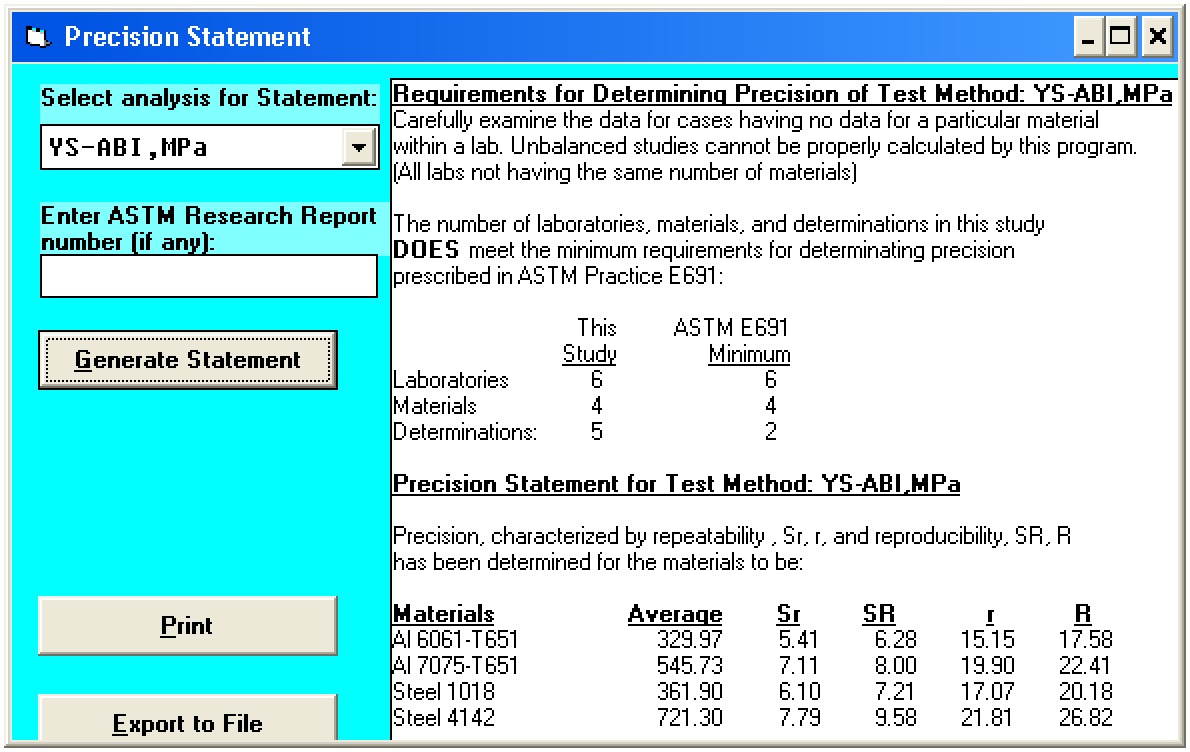
Chairman (ASTM Z9896Z), RR: E-28 XXXX

Analysis: UD-ABI (%)

Laboratory	Al 6061-T651	Al-7075-T651	Steel 1018	Steel 4142
	9.30	7.10	10.20	10.50
	6.90	5.50	10.10	10.50
	6.40	5.60	10.00	9.90
4	6.80	5.30	10.30	10.20
	8.70	5.50	10.00	10.50
	6.50	5.70	10.20	10.30
	6.60	5.20	10.30	10.10
	6.20	5.20	10.50	10.50
5	6.80	5.90	10.70	10.60
	6.70	5.60	10.10	10.50
	6.80	5.50	10.40	10.50
	6.40	5.50	10.20	10.10
	7.00	6.10	10.40	10.50
6	6.80	6.50	10.40	10.10
	8.60	5.60	10.70	10.30
	8.70	5.90	10.40	10.30
	9.00	5.80	10.20	10.50
	8.50	5.70	10.80	10.30

Table 2A – Precision Summary for the ABI-Determined Yield Strength (YS-ABI), MPa



Select analysis for Statement: YS-ABI,MPa

Requirements for Determining Precision of Test Method: YS-ABI,MPa

Carefully examine the data for cases having no data for a particular material within a lab. Unbalanced studies cannot be properly calculated by this program. (All labs not having the same number of materials)

The number of laboratories, materials, and determinations in this study **DOES** meet the minimum requirements for determinating precision prescribed in ASTM Practice E691:

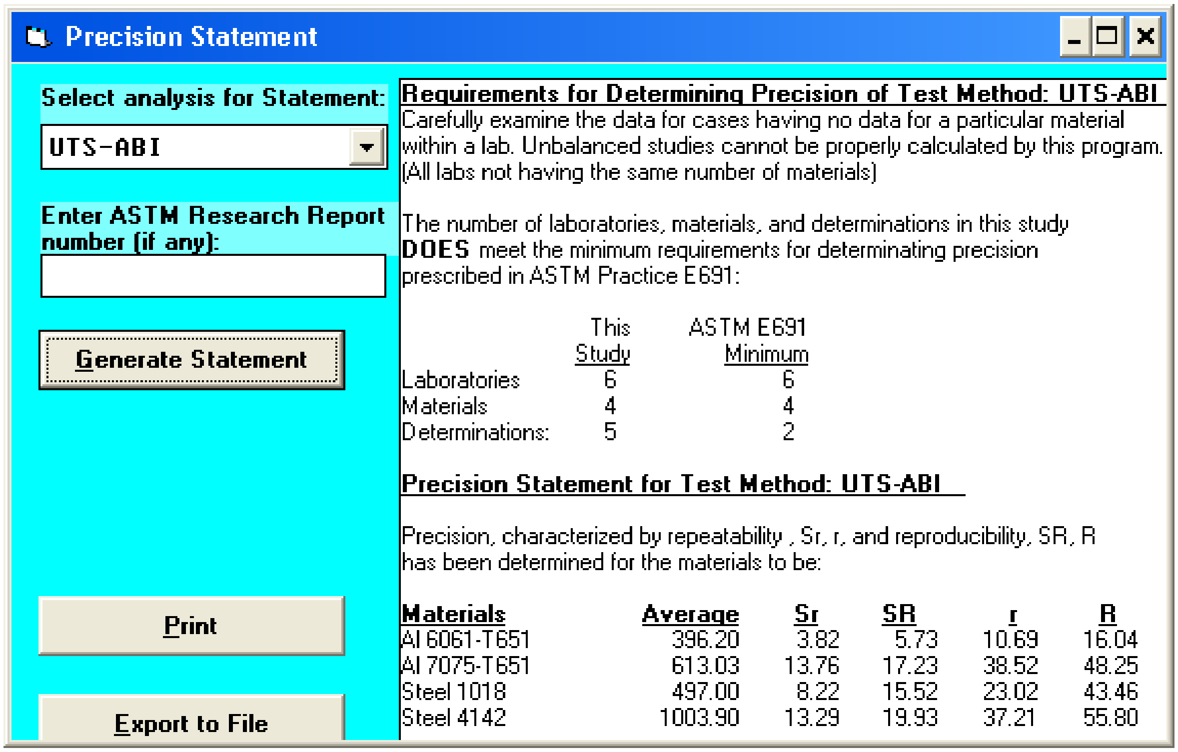
	This Study	ASTM E691 Minimum
Laboratories	6	6
Materials	4	4
Determinations:	5	2

Precision Statement for Test Method: YS-ABI,MPa

Precision, characterized by repeatability , Sr, r, and reproducibility, SR, R has been determined for the materials to be:

Materials	Average	Sr	SR	r	R
Al 6061-T651	329.97	5.41	6.28	15.15	17.58
Al 7075-T651	545.73	7.11	8.00	19.90	22.41
Steel 1018	361.90	6.10	7.21	17.07	20.18
Steel 4142	721.30	7.79	9.58	21.81	26.82

Table 2B – Precision Summary for the ABI-Estimated Ultimate Strength (UTS-ABI), MPa



Select analysis for Statement: UTS-ABI

Requirements for Determining Precision of Test Method: UTS-ABI

Carefully examine the data for cases having no data for a particular material within a lab. Unbalanced studies cannot be properly calculated by this program. (All labs not having the same number of materials)

The number of laboratories, materials, and determinations in this study **DOES** meet the minimum requirements for determinating precision prescribed in ASTM Practice E691:

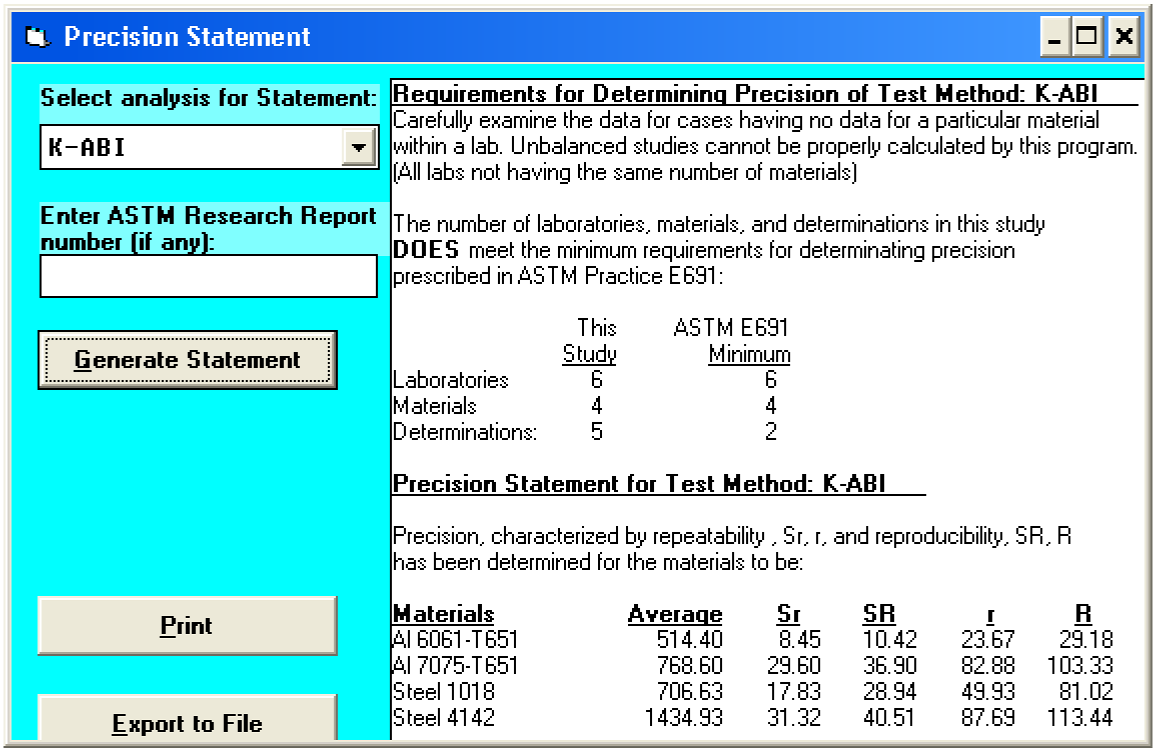
	This Study	ASTM E691 Minimum
Laboratories	6	6
Materials	4	4
Determinations:	5	2

Precision Statement for Test Method: UTS-ABI

Precision, characterized by repeatability , Sr, r, and reproducibility, SR, R has been determined for the materials to be:

Materials	Average	Sr	SR	r	R
Al 6061-T651	396.20	3.82	5.73	10.69	16.04
Al 7075-T651	613.03	13.76	17.23	38.52	48.25
Steel 1018	497.00	8.22	15.52	23.02	43.46
Steel 4142	1003.90	13.29	19.93	37.21	55.80

Table 2C – Precision Summary for the ABI-Determined Strength Coefficient (K-ABI), MPa



Select analysis for Statement: K-ABI

Requirements for Determining Precision of Test Method: K-ABI

Carefully examine the data for cases having no data for a particular material within a lab. Unbalanced studies cannot be properly calculated by this program. (All labs not having the same number of materials)

The number of laboratories, materials, and determinations in this study **DOES** meet the minimum requirements for determinating precision prescribed in ASTM Practice E691:

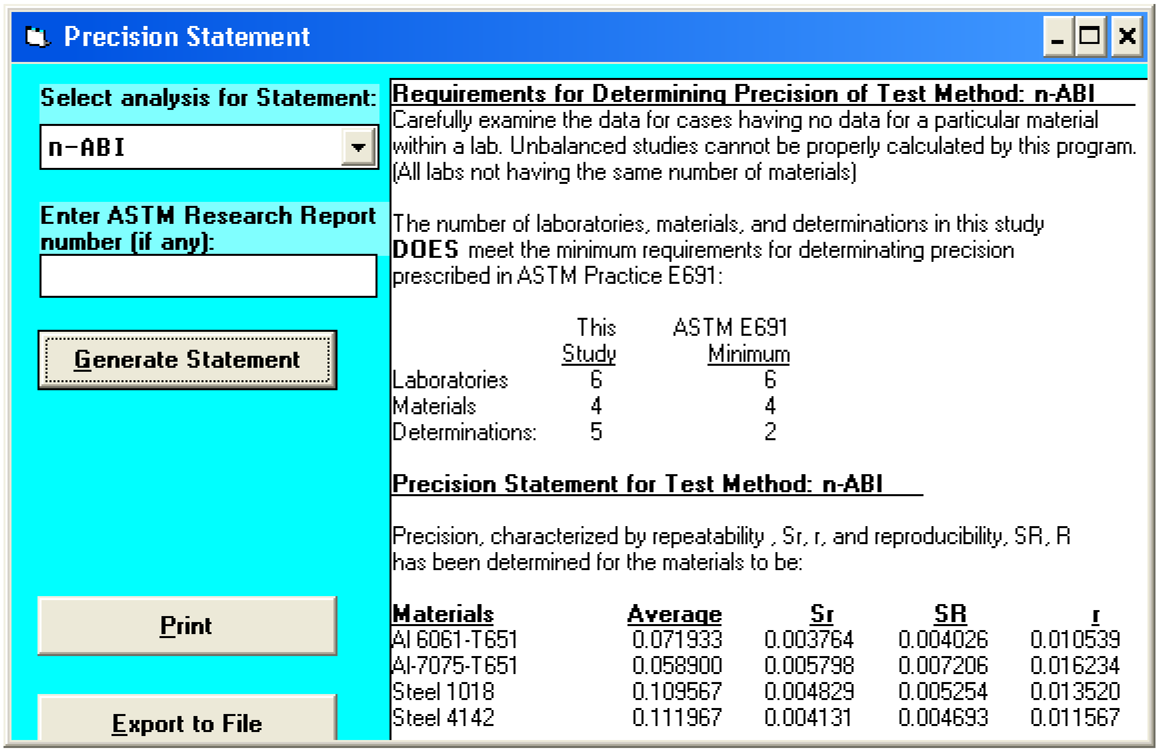
	This Study	ASTM E691 Minimum
Laboratories	6	6
Materials	4	4
Determinations:	5	2

Precision Statement for Test Method: K-ABI

Precision, characterized by repeatability , Sr, r, and reproducibility, SR, R has been determined for the materials to be:

Materials	Average	Sr	SR	r	R
Al 6061-T651	514.40	8.45	10.42	23.67	29.18
Al 7075-T651	768.60	29.60	36.90	82.88	103.33
Steel 1018	706.63	17.83	28.94	49.93	81.02
Steel 4142	1434.93	31.32	40.51	87.69	113.44

Table 2D – Precision Summary for the ABI-Determined Strain-Hardening Exponent (n-ABI)



Select analysis for Statement: n-ABI

Requirements for Determining Precision of Test Method: n-ABI

Carefully examine the data for cases having no data for a particular material within a lab. Unbalanced studies cannot be properly calculated by this program. (All labs not having the same number of materials)

The number of laboratories, materials, and determinations in this study **DOES** meet the minimum requirements for determinating precision prescribed in ASTM Practice E691:

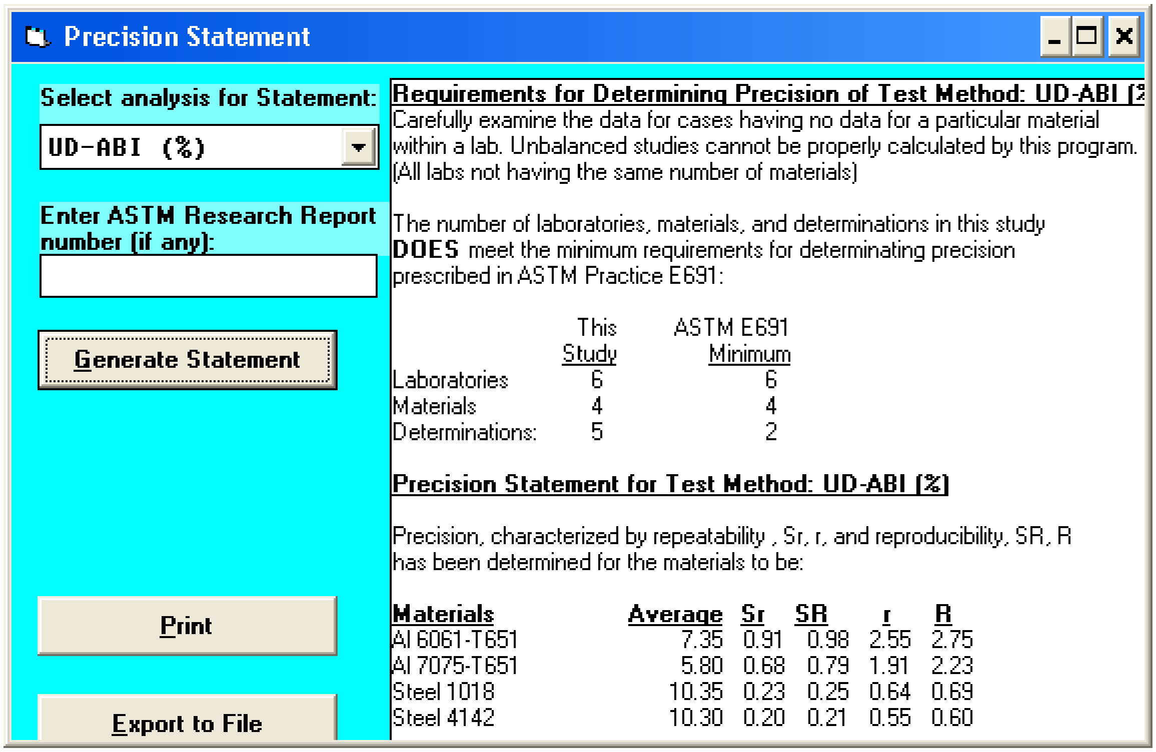
	This Study	ASTM E691 Minimum
Laboratories	6	6
Materials	4	4
Determinations:	5	2

Precision Statement for Test Method: n-ABI

Precision, characterized by repeatability , Sr, r, and reproducibility, SR, R has been determined for the materials to be:

Materials	Average	Sr	SR	r
Al 6061-T651	0.071933	0.003764	0.004026	0.010539
Al-7075-T651	0.058900	0.005798	0.007206	0.016234
Steel 1018	0.109567	0.004829	0.005254	0.013520
Steel 4142	0.111967	0.004131	0.004693	0.011567

Table 2E – Precision Summary for the ABI-Calculated Uniform Ductility (UD-ABI), percent



Select analysis for Statement: UD-ABI (%)

Enter ASTM Research Report number (if any):

Requirements for Determining Precision of Test Method: UD-ABI (

Carefully examine the data for cases having no data for a particular material within a lab. Unbalanced studies cannot be properly calculated by this program. (All labs not having the same number of materials)

The number of laboratories, materials, and determinations in this study **DOES** meet the minimum requirements for determinating precision prescribed in ASTM Practice E691:

	This Study	ASTM E691 Minimum
Laboratories	6	6
Materials	4	4
Determinations:	5	2

Precision Statement for Test Method: UD-ABI (%)

Precision, characterized by repeatability , Sr, r, and reproducibility, SR, R has been determined for the materials to be:

Materials	Average	Sr	SR	r	R
Al 6061-T651	7.35	0.91	0.98	2.55	2.75
Al 7075-T651	5.80	0.68	0.79	1.91	2.23
Steel 1018	10.35	0.23	0.25	0.64	0.69
Steel 4142	10.30	0.20	0.21	0.55	0.60

Table 3A – Precision Summary for the ABI-Determined Yield Strength (YS-ABI), MPa or Percent

Precision, characterized by repeatability, Sr, r, and reproducibility, SR, R has been determined for the materials to be:

Materials	Average	Sr	CV $\%_r$	SR	CV $\%_R$	r	R
Al 6061-T651	329.97	5.41	1.64	6.28	1.90	15.15	17.58
Al 7075-T651	545.73	7.11	1.30	8.00	1.47	19.90	22.41
Steel 1018	361.90	6.10	1.69	7.21	1.99	17.07	20.18
Steel 4142	721.30	7.79	1.08	9.58	1.33	21.81	26.82
Average			**1.4**		**1.7**		

CV $\%_r$ = repeatability coefficient of variation in percent within a laboratory
CV $\%_R$ = repeatability coefficient of variation in percent between laboratories

Notes: The individual value of CV $\%_r$ for each material is obtained by dividing the individual Sr value by the average value for the material (e.g., for Al 6061-T651: 5.41/329.97 = 1.64).

The average CV $\%_r$ for all four materials is obtained by dividing the sum of the four individual CV $\%_r$ values by the number of materials [e.g., (1.64 + 1.30 + 1.69 + 1.08)/4 = 1.4].

The same approach is used for the Average CV $\%_R$.

The ASTM E691 Software provides only the precision analysis shown in Table 2. Table 3 has the same data of Table 2 with the additional CV $\%_r$ and CV $\%_R$ analyses as was done in Table 2 of the RR: E28-1004 (dated 3/30/84). This additional analysis is also shown in the Precision Statement of Section 9.1 of the ASTM Standard E 8-00 "Standard Test Methods for Tension Testing of Metallic Materials."

Table 3B – Precision Summary for the ABI-Estimated Ultimate Strength (UTS-ABI), MPa or Percent

Precision, characterized by repeatability, Sr, r, and reproducibility, SR, R has been determined for the materials to be:

Materials	Average	Sr	CV $\%_r$	SR	CV $\%_R$	r	R
Al 6061-T651	396.20	3.82	0.96	5.73	1.45	10.69	16.04
Al 7075-T651	613.03	13.76	2.24	17.23	2.81	38.52	48.25
Steel 1018	497.00	8.22	1.65	15.52	3.12	23.02	43.46
Steel 4142	1003.90	13.29	1.32	19.93	1.99	37.21	55.80
Average			**1.5**		**2.3**		

CV $\%_r$ = repeatability coefficient of variation in percent within a laboratory
CV $\%_R$ = repeatability coefficient of variation in percent between laboratories

Table 3C – Precision Summary for the ABI-Determined Strength Coefficient (K-ABI), MPa or Percent

Precision, characterized by repeatability, Sr, r, and reproducibility, SR, R, has been determined for the following materials to be:

Materials	Average	Sr	CV $\%_r$	SR	CV $\%_R$	r	R
Al 6061-T651	514.40	8.45	1.64	10.42	2.03	23.67	29.18
Al-7075-T651	768.60	29.60	3.85	36.90	4.80	82.88	103.33
Steel 1018	706.63	17.83	2.52	28.94	4.10	49.93	81.02
Steel 4142	1434.93	31.32	2.18	40.51	2.82	87.69	113.44
Average			**2.6**		**3.4**		

CV $\%_r$ = repeatability coefficient of variation in percent within a laboratory
CV $\%_R$ = repeatability coefficient of variation in percent between laboratories

Table 3D – Precision Summary for the ABI-Determined Strain-Hardening Exponent (n-ABI), Dimensionless or Percent

Precision, characterized by repeatability, Sr, r, and reproducibility, SR, R, has been determined for the following materials to be:

Materials	Average	Sr	CV $\%_r$	SR	CV $\%_R$	r	R
Al 6061-T651	0.071933	0.003764	5.23	0.004026	5.60	0.010539	0.011273
Al-7075-T651	0.058900	0.005798	9.84	0.007206	12.23	0.016234	0.020177
Steel 1018	0.109567	0.004829	4.41	0.005254	4.80	0.013520	0.014711
Steel 4142	0.111967	0.004131	3.69	0.004693	4.19	0.011567	0.013142
Average			**5.8**		**6.7**		

CV $\%_r$ = repeatability coefficient of variation in percent within a laboratory
CV $\%_R$ = repeatability coefficient of variation in percent between laboratories

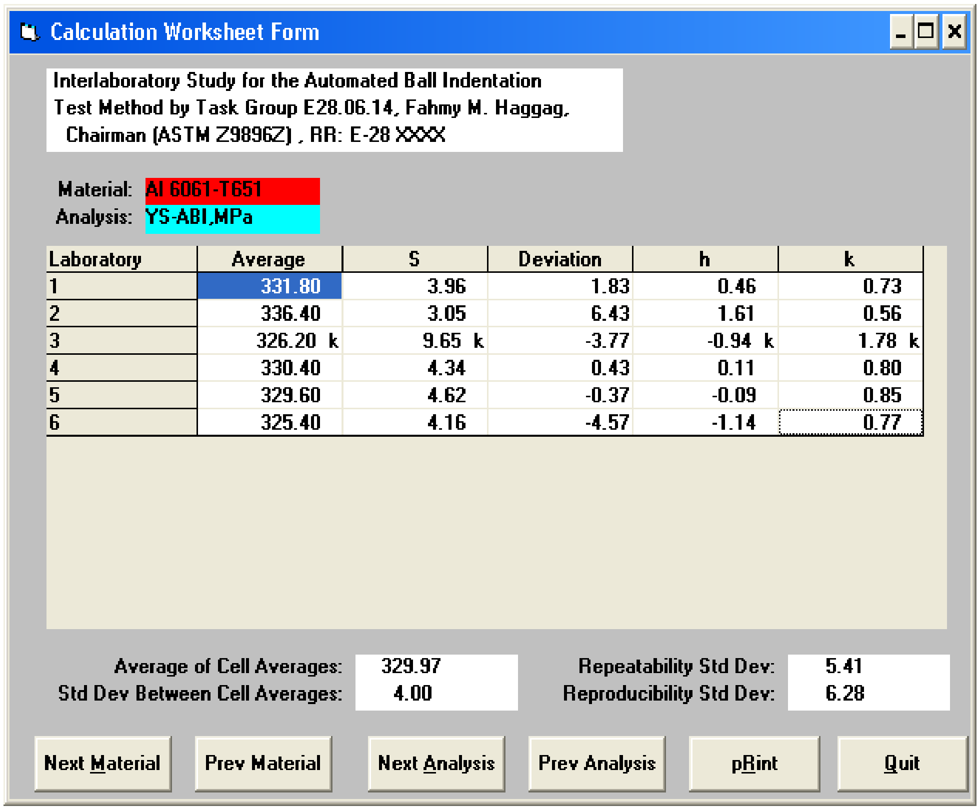
Table 3E – Precision Summary for the ABI-Calculated Uniform Ductility (UD-ABI)

Precision, characterized by repeatability, Sr, r, and reproducibility, SR, R has been determined for the materials to be:

Materials	Average	Sr	CV $\%_r$	SR	CV $\%_R$	r	R
Al 6061-T651	7.41	0.88	11.88	0.98	13.22	2.47	2.74
Al 7075-T651	5.80	0.68	11.72	0.79	13.62	1.91	2.23
Steel 1018	10.35	0.23	2.22	0.25	2.42	0.64	0.69
Steel 4142	10.30	0.20	1.94	0.21	2.04	0.55	0.60
Average			**6.9**		**7.8**		

CV $\%_r$ = repeatability coefficient of variation in percent within a laboratory
CV $\%_R$ = repeatability coefficient of variation in percent between laboratories

Table 4A- Calculation Worksheet of the Individual Laboratories for the YS-ABI by material, MPa

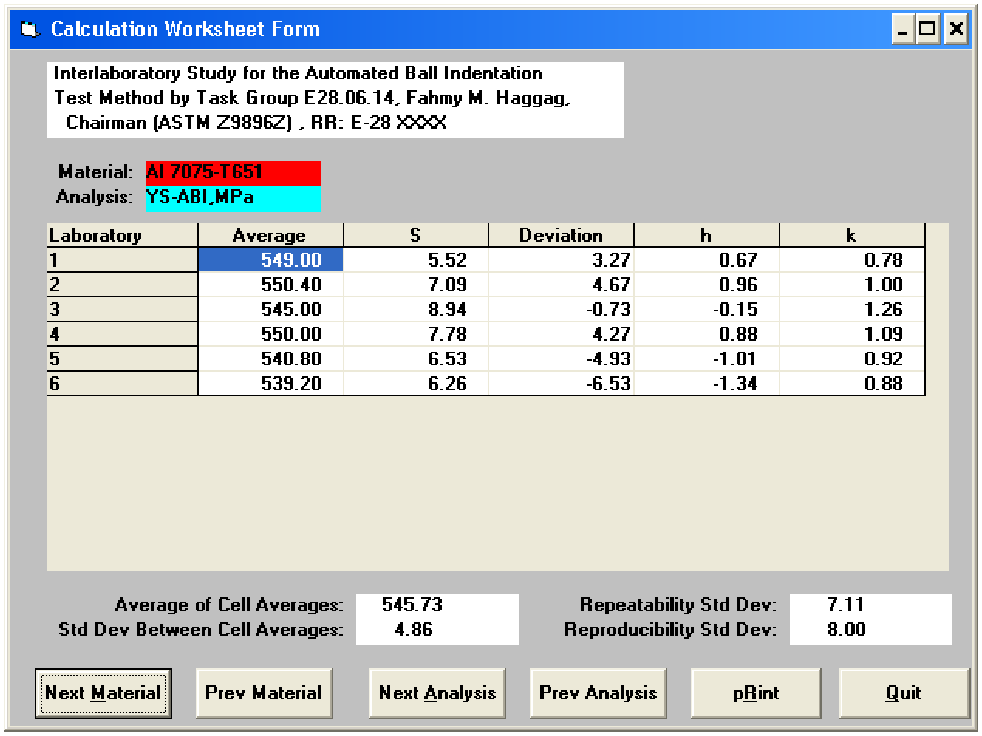


Interlaboratory Study for the Automated Ball Indentation
Test Method by Task Group E28.06.14, Fahmy M. Haggag,
Chairman (ASTM Z9896Z) , RR: E-28 XXXX

Material: Al 6061-T651
Analysis: YS-ABI,MPa

Laboratory	Average	S	Deviation	h	k
1	331.80	3.96	1.83	0.46	0.73
2	336.40	3.05	6.43	1.61	0.56
3	326.20 k	9.65 k	-3.77	-0.94 k	1.78 k
4	330.40	4.34	0.43	0.11	0.80
5	329.60	4.62	-0.37	-0.09	0.85
6	325.40	4.16	-4.57	-1.14	0.77

Average of Cell Averages: 329.97
Std Dev Between Cell Averages: 4.00
Repeatability Std Dev: 5.41
Reproducibility Std Dev: 6.28

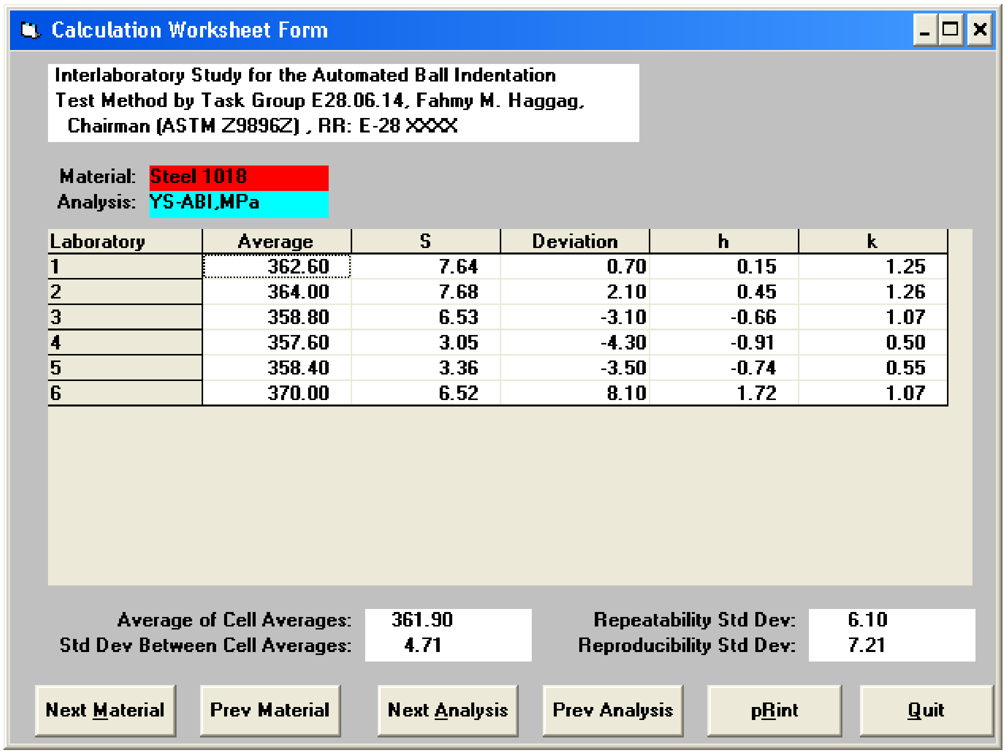


Interlaboratory Study for the Automated Ball Indentation
Test Method by Task Group E28.06.14, Fahmy M. Haggag,
Chairman (ASTM Z9896Z) , RR: E-28 XXXX

Material: Al 7075-T651
Analysis: YS-ABI,MPa

Laboratory	Average	S	Deviation	h	k
1	549.00	5.52	3.27	0.67	0.78
2	550.40	7.09	4.67	0.96	1.00
3	545.00	8.94	-0.73	-0.15	1.26
4	550.00	7.78	4.27	0.88	1.09
5	540.80	6.53	-4.93	-1.01	0.92
6	539.20	6.26	-6.53	-1.34	0.88

Average of Cell Averages: 545.73
Std Dev Between Cell Averages: 4.86
Repeatability Std Dev: 7.11
Reproducibility Std Dev: 8.00

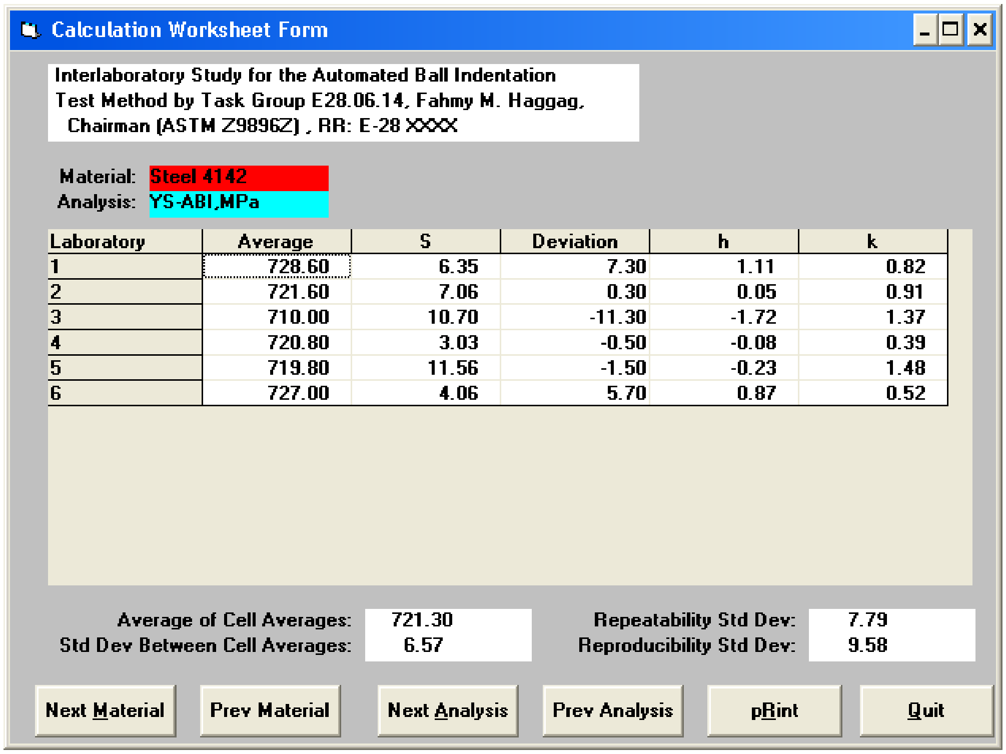


Interlaboratory Study for the Automated Ball Indentation
Test Method by Task Group E28.06.14, Fahmy M. Haggag,
Chairman (ASTM Z9896Z) , RR: E-28 XXXX

Material: Steel 1018
Analysis: YS-ABI,MPa

Laboratory	Average	S	Deviation	h	k
1	362.60	7.64	0.70	0.15	1.25
2	364.00	7.68	2.10	0.45	1.26
3	358.80	6.53	-3.10	-0.66	1.07
4	357.60	3.05	-4.30	-0.91	0.50
5	358.40	3.36	-3.50	-0.74	0.55
6	370.00	6.52	8.10	1.72	1.07

Average of Cell Averages: 361.90
Std Dev Between Cell Averages: 4.71
Repeatability Std Dev: 6.10
Reproducibility Std Dev: 7.21



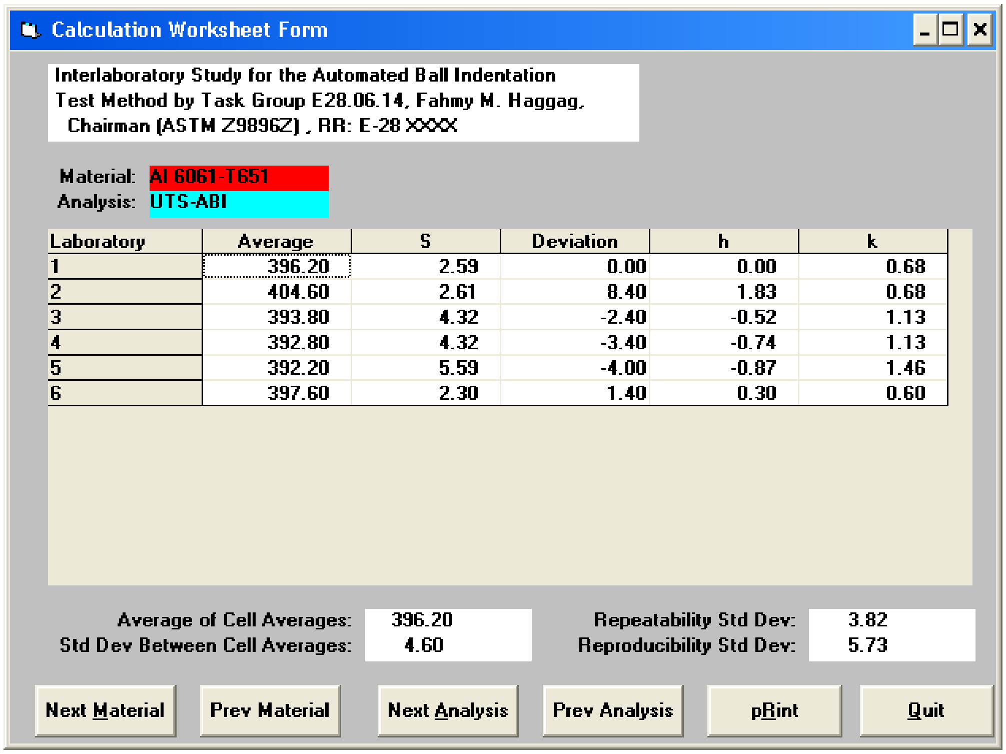
Interlaboratory Study for the Automated Ball Indentation
Test Method by Task Group E28.06.14, Fahmy M. Haggag,
Chairman (ASTM Z9896Z) , RR: E-28 XXXX

Material: Steel 4142
Analysis: YS-ABI,MPa

Laboratory	Average	S	Deviation	h	k
1	728.60	6.35	7.30	1.11	0.82
2	721.60	7.06	0.30	0.05	0.91
3	710.00	10.70	-11.30	-1.72	1.37
4	720.80	3.03	-0.50	-0.08	0.39
5	719.80	11.56	-1.50	-0.23	1.48
6	727.00	4.06	5.70	0.87	0.52

Average of Cell Averages: 721.30
Std Dev Between Cell Averages: 6.57
Repeatability Std Dev: 7.79
Reproducibility Std Dev: 9.58

Table 4B- Calculation Worksheet of the Individual Laboratories for the UTS-ABI by material, MPa

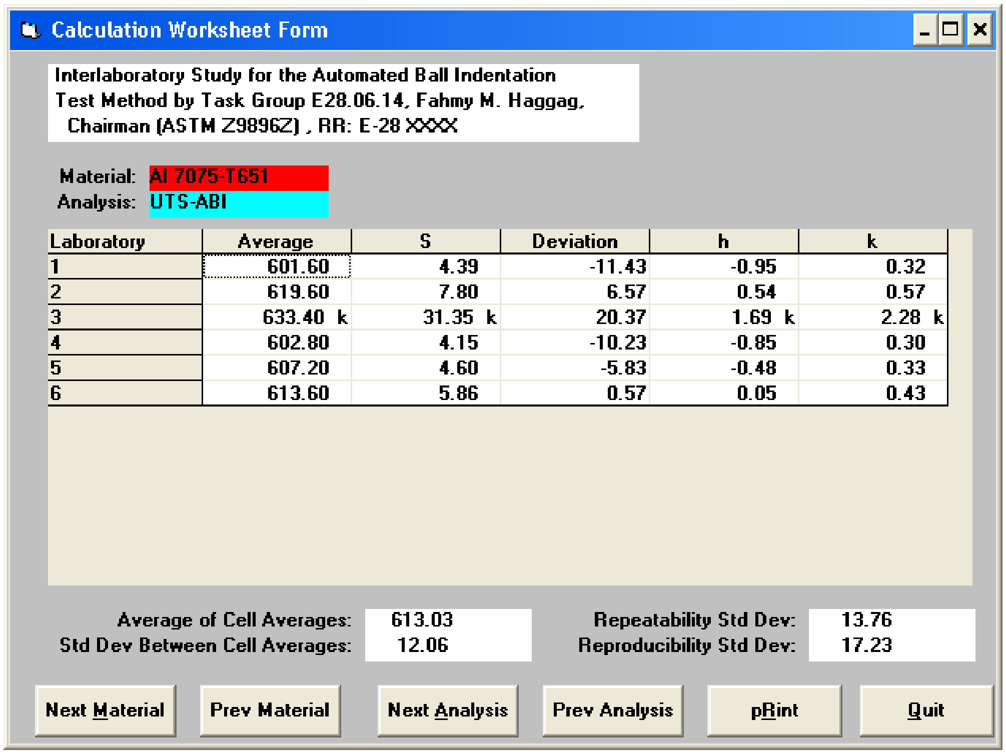


Interlaboratory Study for the Automated Ball Indentation
Test Method by Task Group E28.06.14, Fahmy M. Haggag,
Chairman (ASTM Z9896Z) , RR: E-28 XXXX

Material: Al 6061-T651
Analysis: UTS-ABI

Laboratory	Average	S	Deviation	h	k
1	396.20	2.59	0.00	0.00	0.68
2	404.60	2.61	8.40	1.83	0.68
3	393.80	4.32	-2.40	-0.52	1.13
4	392.80	4.32	-3.40	-0.74	1.13
5	392.20	5.59	-4.00	-0.87	1.46
6	397.60	2.30	1.40	0.30	0.60

Average of Cell Averages: 396.20
Std Dev Between Cell Averages: 4.60
Repeatability Std Dev: 3.82
Reproducibility Std Dev: 5.73

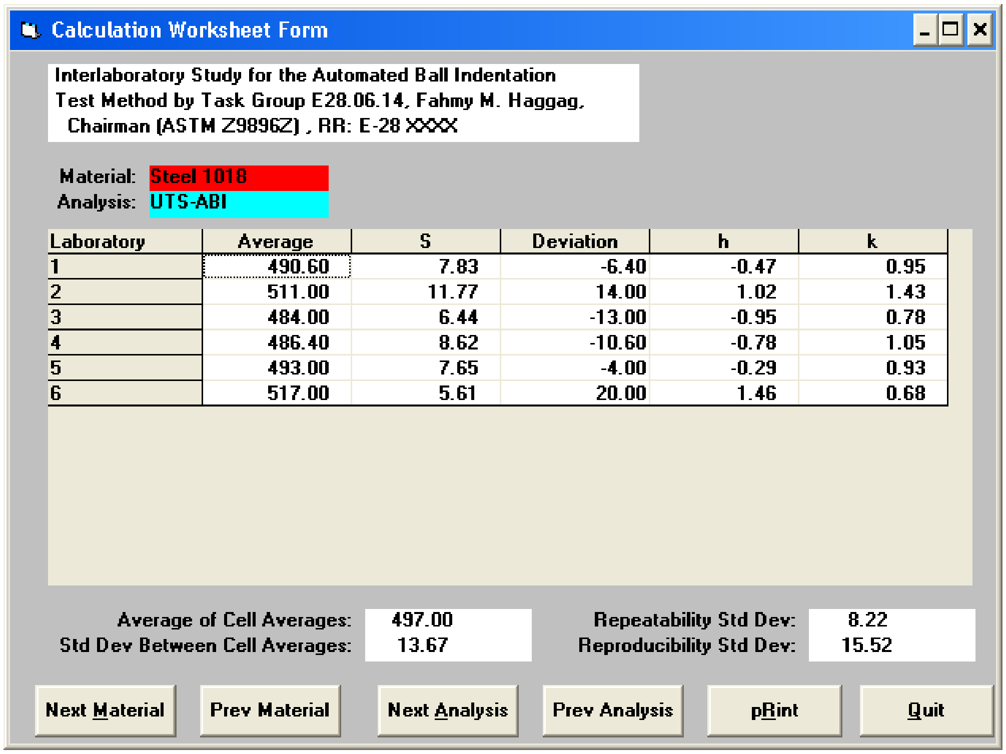


Interlaboratory Study for the Automated Ball Indentation
Test Method by Task Group E28.06.14, Fahmy M. Haggag,
Chairman (ASTM Z9896Z) , RR: E-28 XXXX

Material: Al 7075-T651
Analysis: UTS-ABI

Laboratory	Average	S	Deviation	h	k
1	601.60	4.39	-11.43	-0.95	0.32
2	619.60	7.80	6.57	0.54	0.57
3	633.40 k	31.35 k	20.37	1.69 k	2.28 k
4	602.80	4.15	-10.23	-0.85	0.30
5	607.20	4.60	-5.83	-0.48	0.33
6	613.60	5.86	0.57	0.05	0.43

Average of Cell Averages: 613.03
Std Dev Between Cell Averages: 12.06
Repeatability Std Dev: 13.76
Reproducibility Std Dev: 17.23

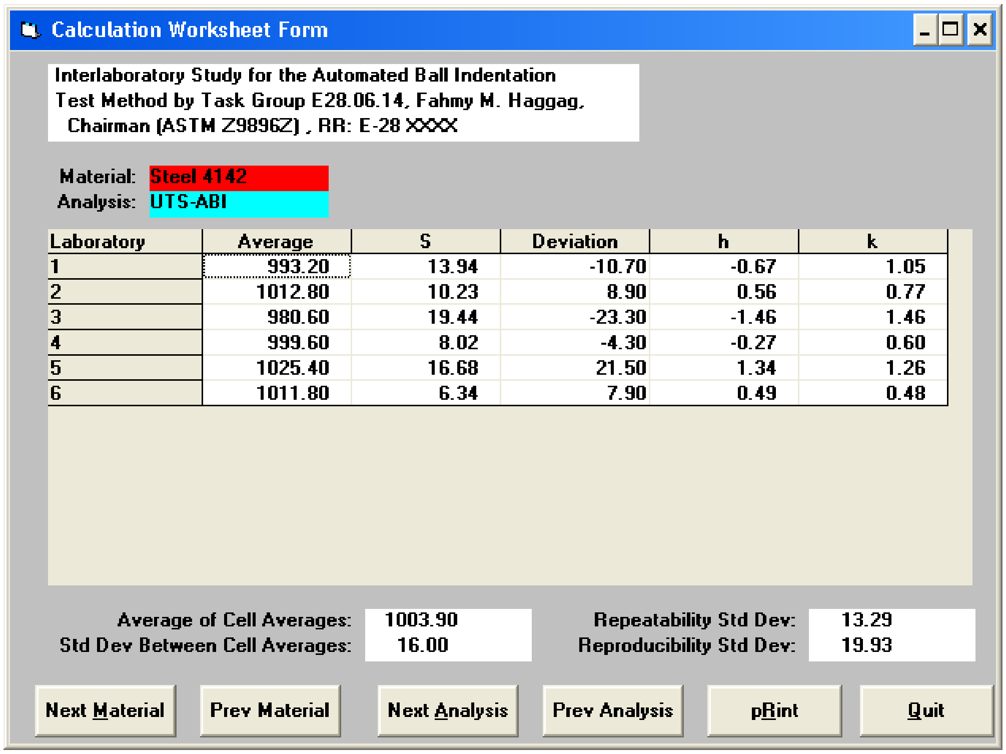


Interlaboratory Study for the Automated Ball Indentation
Test Method by Task Group E28.06.14, Fahmy M. Haggag,
Chairman (ASTM Z9896Z) , RR: E-28 XXXX

Material: Steel 1018
Analysis: UTS-ABI

Laboratory	Average	S	Deviation	h	k
1	490.60	7.83	-6.40	-0.47	0.95
2	511.00	11.77	14.00	1.02	1.43
3	484.00	6.44	-13.00	-0.95	0.78
4	486.40	8.62	-10.60	-0.78	1.05
5	493.00	7.65	-4.00	-0.29	0.93
6	517.00	5.61	20.00	1.46	0.68

Average of Cell Averages: 497.00
Std Dev Between Cell Averages: 13.67
Repeatability Std Dev: 8.22
Reproducibility Std Dev: 15.52



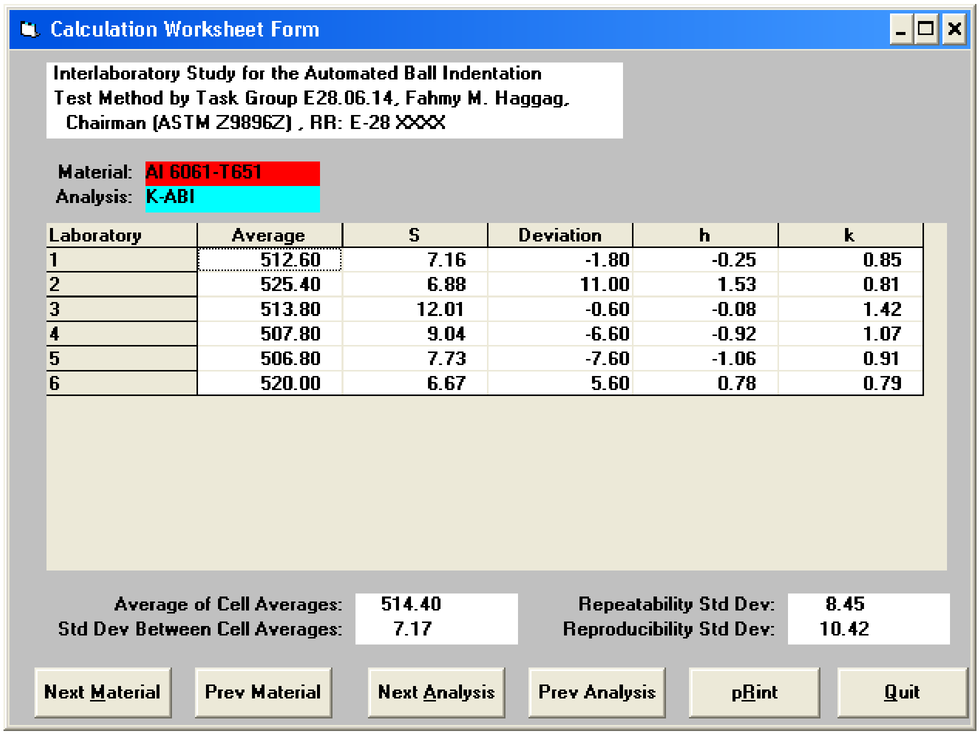
Interlaboratory Study for the Automated Ball Indentation
Test Method by Task Group E28.06.14, Fahmy M. Haggag,
Chairman (ASTM Z9896Z) , RR: E-28 XXXX

Material: Steel 4142
Analysis: UTS-ABI

Laboratory	Average	S	Deviation	h	k
1	993.20	13.94	-10.70	-0.67	1.05
2	1012.80	10.23	8.90	0.56	0.77
3	980.60	19.44	-23.30	-1.46	1.46
4	999.60	8.02	-4.30	-0.27	0.60
5	1025.40	16.68	21.50	1.34	1.26
6	1011.80	6.34	7.90	0.49	0.48

Average of Cell Averages: 1003.90
Std Dev Between Cell Averages: 16.00
Repeatability Std Dev: 13.29
Reproducibility Std Dev: 19.93

Table 4C- Calculation Worksheet of the Individual Laboratories for the K-ABI by material, MPa

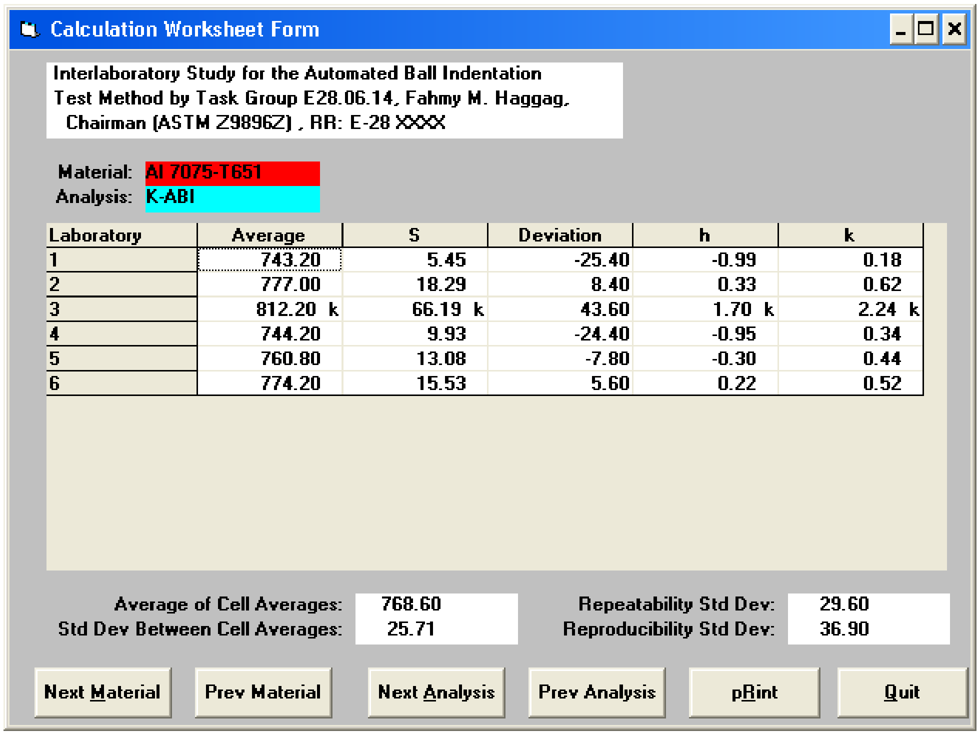


Interlaboratory Study for the Automated Ball Indentation
Test Method by Task Group E28.06.14, Fahmy M. Haggag,
Chairman (ASTM Z9896Z) , RR: E-28 XXXX

Material: Al 6061-T651
Analysis: K-ABI

Laboratory	Average	S	Deviation	h	k
1	512.60	7.16	-1.80	-0.25	0.85
2	525.40	6.88	11.00	1.53	0.81
3	513.80	12.01	-0.60	-0.08	1.42
4	507.80	9.04	-6.60	-0.92	1.07
5	506.80	7.73	-7.60	-1.06	0.91
6	520.00	6.67	5.60	0.78	0.79

Average of Cell Averages: 514.40
Std Dev Between Cell Averages: 7.17
Repeatability Std Dev: 8.45
Reproducibility Std Dev: 10.42

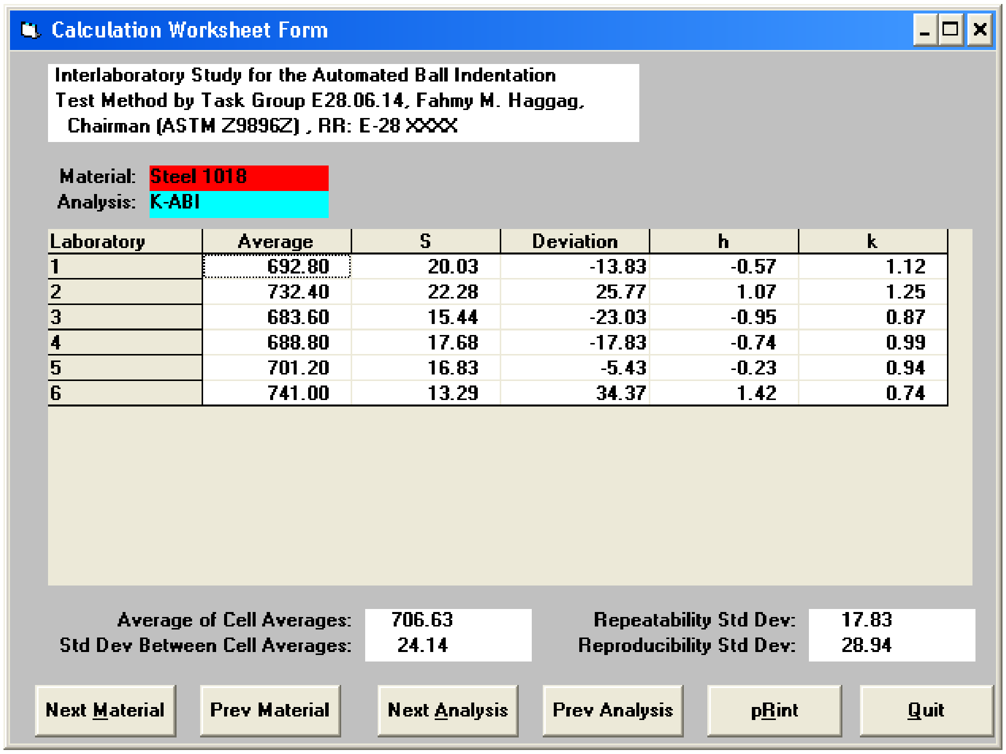


Interlaboratory Study for the Automated Ball Indentation
Test Method by Task Group E28.06.14, Fahmy M. Haggag,
Chairman (ASTM Z9896Z) , RR: E-28 XXXX

Material: Al 7075-T651
Analysis: K-ABI

Laboratory	Average	S	Deviation	h	k
1	743.20	5.45	-25.40	-0.99	0.18
2	777.00	18.29	8.40	0.33	0.62
3	812.20 k	66.19 k	43.60	1.70 k	2.24 k
4	744.20	9.93	-24.40	-0.95	0.34
5	760.80	13.08	-7.80	-0.30	0.44
6	774.20	15.53	5.60	0.22	0.52

Average of Cell Averages: 768.60
Std Dev Between Cell Averages: 25.71
Repeatability Std Dev: 29.60
Reproducibility Std Dev: 36.90

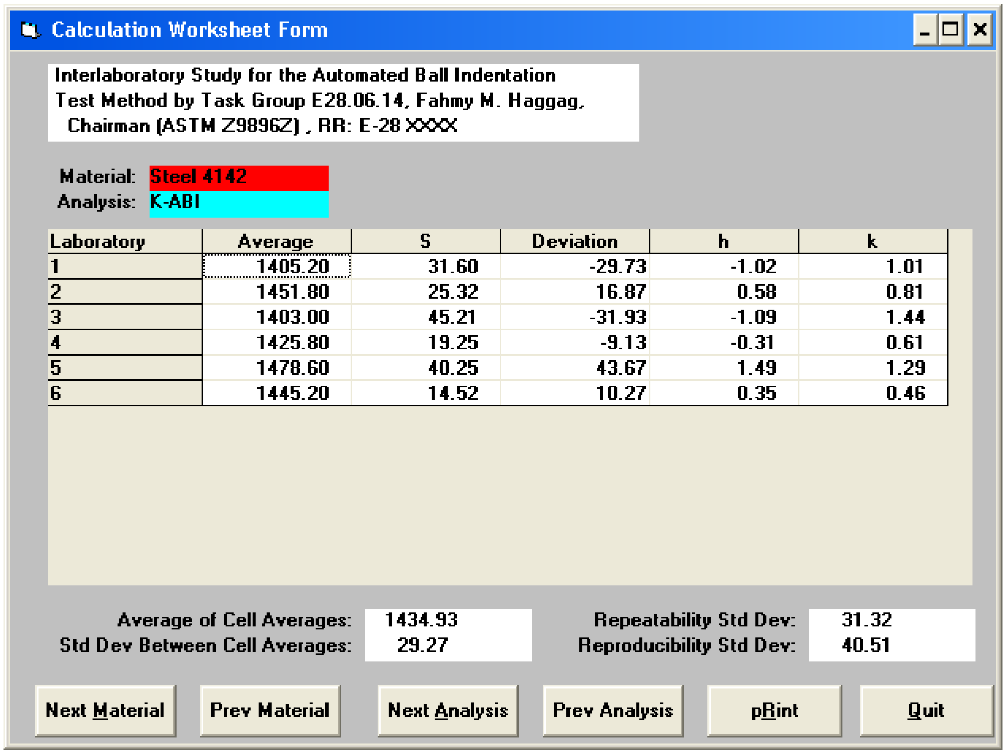


Interlaboratory Study for the Automated Ball Indentation
Test Method by Task Group E28.06.14, Fahmy M. Haggag,
Chairman (ASTM Z9896Z) , RR: E-28 XXXX

Material: Steel 1018
Analysis: K-ABI

Laboratory	Average	S	Deviation	h	k
1	692.80	20.03	-13.83	-0.57	1.12
2	732.40	22.28	25.77	1.07	1.25
3	683.60	15.44	-23.03	-0.95	0.87
4	688.80	17.68	-17.83	-0.74	0.99
5	701.20	16.83	-5.43	-0.23	0.94
6	741.00	13.29	34.37	1.42	0.74

Average of Cell Averages: 706.63
Std Dev Between Cell Averages: 24.14
Repeatability Std Dev: 17.83
Reproducibility Std Dev: 28.94



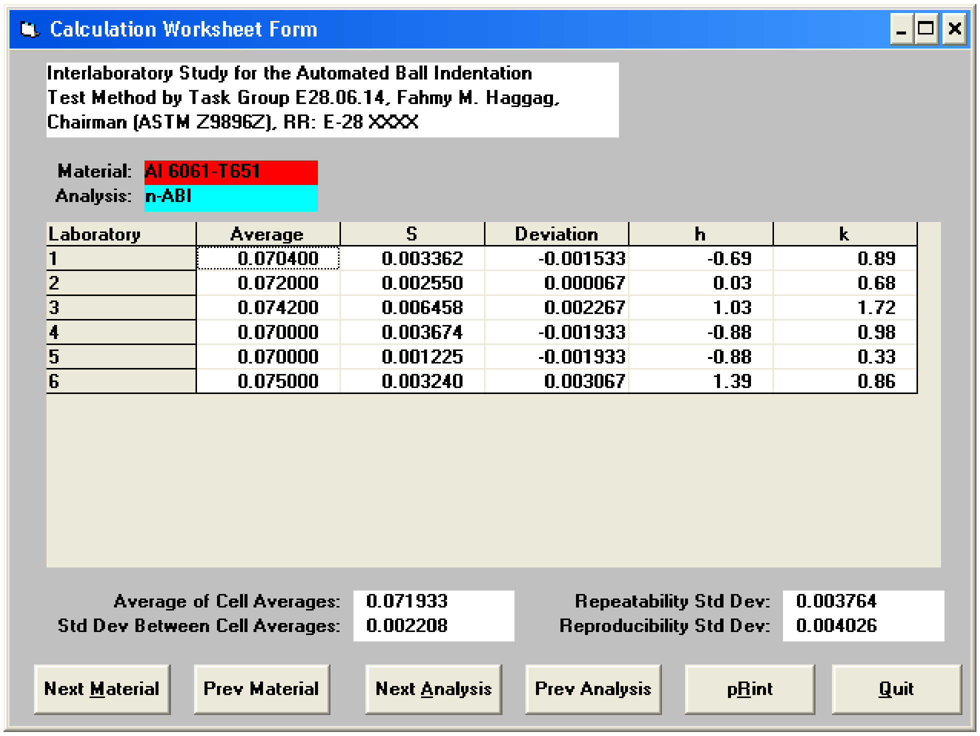
Interlaboratory Study for the Automated Ball Indentation
Test Method by Task Group E28.06.14, Fahmy M. Haggag,
Chairman (ASTM Z9896Z) , RR: E-28 XXXX

Material: Steel 4142
Analysis: K-ABI

Laboratory	Average	S	Deviation	h	k
1	1405.20	31.60	-29.73	-1.02	1.01
2	1451.80	25.32	16.87	0.58	0.81
3	1403.00	45.21	-31.93	-1.09	1.44
4	1425.80	19.25	-9.13	-0.31	0.61
5	1478.60	40.25	43.67	1.49	1.29
6	1445.20	14.52	10.27	0.35	0.46

Average of Cell Averages: 1434.93
Std Dev Between Cell Averages: 29.27
Repeatability Std Dev: 31.32
Reproducibility Std Dev: 40.51

Table 4D- Calculation Worksheet of the Individual Laboratories for the n-ABI by material

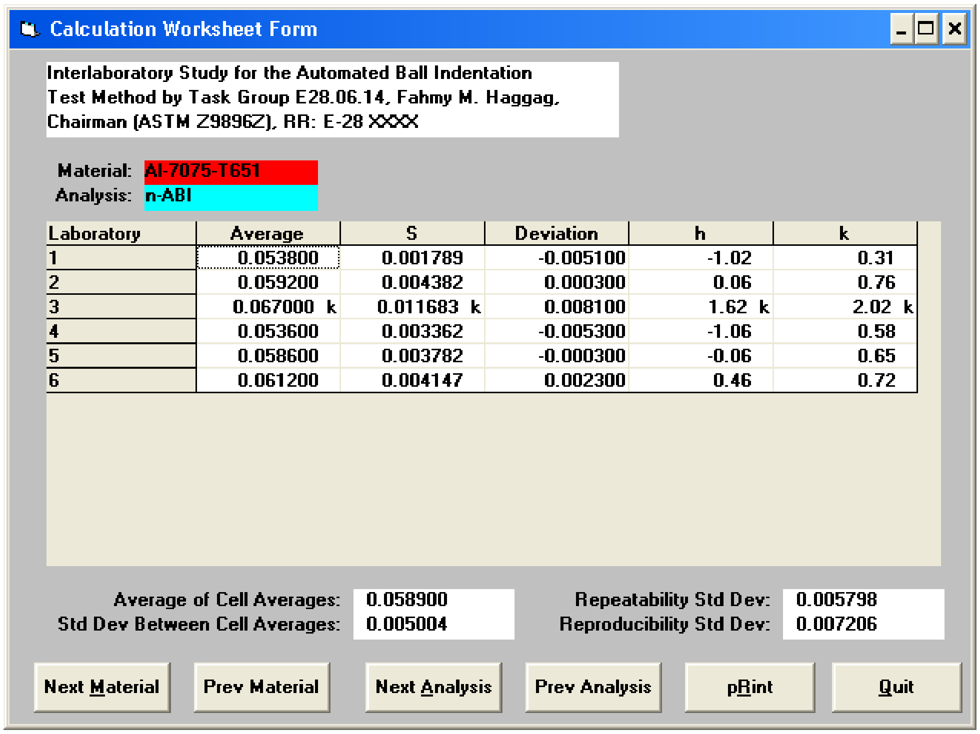


Interlaboratory Study for the Automated Ball Indentation
Test Method by Task Group E28.06.14, Fahmy M. Haggag,
Chairman (ASTM Z9896Z), RR: E-28 XXXX

Material: Al 6061-T651
Analysis: n-ABI

Laboratory	Average	S	Deviation	h	k
1	0.070400	0.003362	-0.001533	-0.69	0.89
2	0.072000	0.002550	0.000067	0.03	0.68
3	0.074200	0.006458	0.002267	1.03	1.72
4	0.070000	0.003674	-0.001933	-0.88	0.98
5	0.070000	0.001225	-0.001933	-0.88	0.33
6	0.075000	0.003240	0.003067	1.39	0.86

Average of Cell Averages: 0.071933
Std Dev Between Cell Averages: 0.002208
Repeatability Std Dev: 0.003764
Reproducibility Std Dev: 0.004026

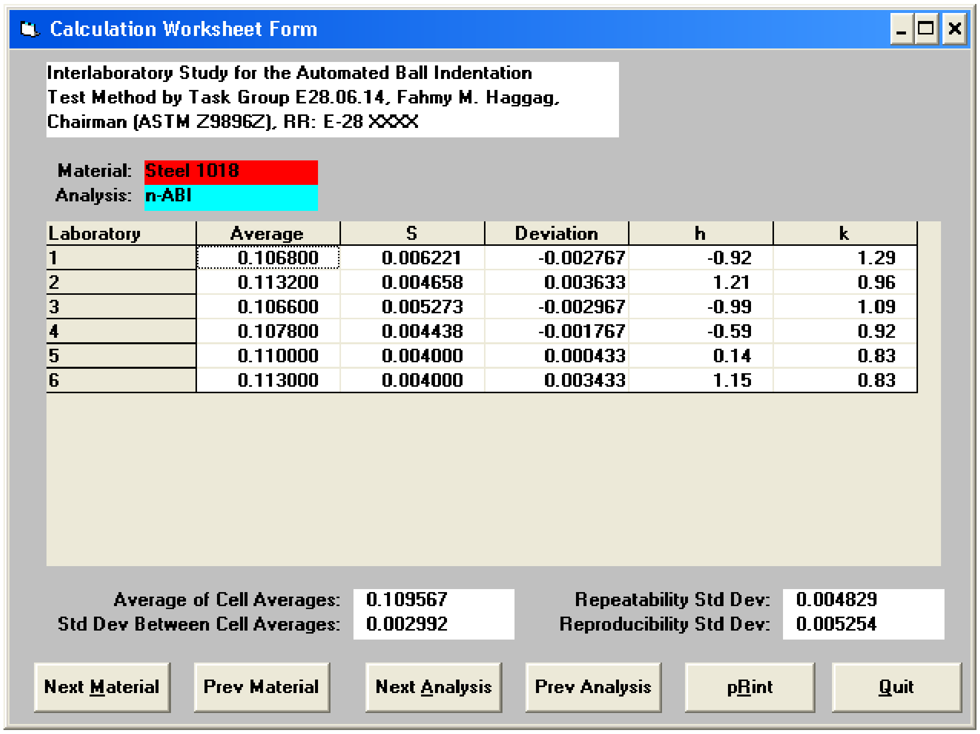


Interlaboratory Study for the Automated Ball Indentation
Test Method by Task Group E28.06.14, Fahmy M. Haggag,
Chairman (ASTM Z9896Z), RR: E-28 XXXX

Material: Al-7075-T651
Analysis: n-ABI

Laboratory	Average	S	Deviation	h	k
1	0.053800	0.001789	-0.005100	-1.02	0.31
2	0.059200	0.004382	0.000300	0.06	0.76
3	0.067000 k	0.011683 k	0.008100	1.62 k	2.02 k
4	0.053600	0.003362	-0.005300	-1.06	0.58
5	0.058600	0.003782	-0.000300	-0.06	0.65
6	0.061200	0.004147	0.002300	0.46	0.72

Average of Cell Averages: 0.058900
Std Dev Between Cell Averages: 0.005004
Repeatability Std Dev: 0.005798
Reproducibility Std Dev: 0.007206

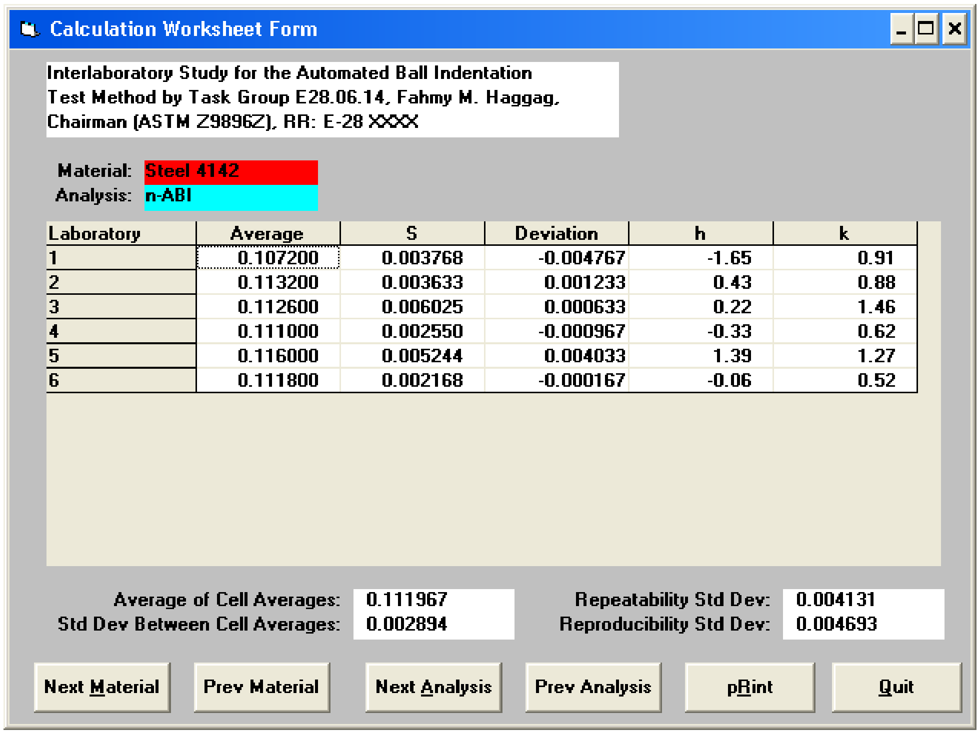


Interlaboratory Study for the Automated Ball Indentation Test Method by Task Group E28.06.14, Fahmy M. Haggag, Chairman (ASTM Z9896Z), RR: E-28 XXXX

Material: Steel 1018
Analysis: n-ABI

Laboratory	Average	S	Deviation	h	k
1	0.106800	0.006221	-0.002767	-0.92	1.29
2	0.113200	0.004658	0.003633	1.21	0.96
3	0.106600	0.005273	-0.002967	-0.99	1.09
4	0.107800	0.004438	-0.001767	-0.59	0.92
5	0.110000	0.004000	0.000433	0.14	0.83
6	0.113000	0.004000	0.003433	1.15	0.83

Average of Cell Averages: 0.109567
Std Dev Between Cell Averages: 0.002992
Repeatability Std Dev: 0.004829
Reproducibility Std Dev: 0.005254



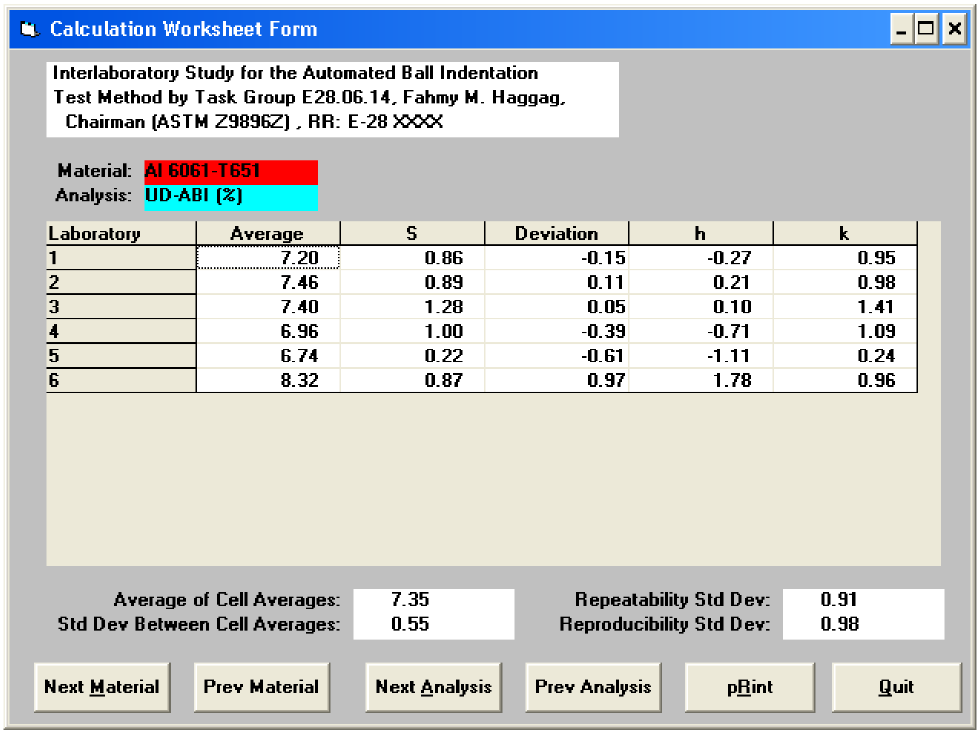
Interlaboratory Study for the Automated Ball Indentation Test Method by Task Group E28.06.14, Fahmy M. Haggag, Chairman (ASTM Z9896Z), RR: E-28 XXXX

Material: Steel 4142
Analysis: n-ABI

Laboratory	Average	S	Deviation	h	k
1	0.107200	0.003768	-0.004767	-1.65	0.91
2	0.113200	0.003633	0.001233	0.43	0.88
3	0.112600	0.006025	0.000633	0.22	1.46
4	0.111000	0.002550	-0.000967	-0.33	0.62
5	0.116000	0.005244	0.004033	1.39	1.27
6	0.111800	0.002168	-0.000167	-0.06	0.52

Average of Cell Averages: 0.111967
Std Dev Between Cell Averages: 0.002894
Repeatability Std Dev: 0.004131
Reproducibility Std Dev: 0.004693

Table 4E- Calculation Worksheet of the Individual Laboratories for the UD-ABI by material, Percent

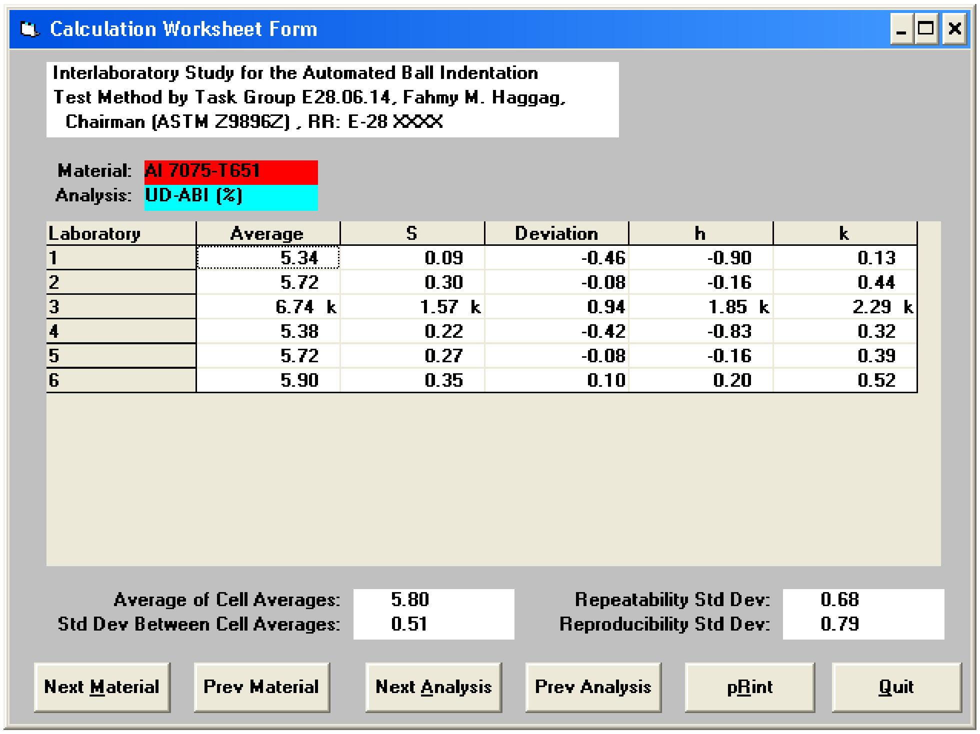


Interlaboratory Study for the Automated Ball Indentation
Test Method by Task Group E28.06.14, Fahmy M. Haggag,
Chairman (ASTM Z9896Z) , RR: E-28 XXXX

Material: Al 6061-T651
Analysis: UD-ABI (%)

Laboratory	Average	S	Deviation	h	k
1	7.20	0.86	-0.15	-0.27	0.95
2	7.46	0.89	0.11	0.21	0.98
3	7.40	1.28	0.05	0.10	1.41
4	6.96	1.00	-0.39	-0.71	1.09
5	6.74	0.22	-0.61	-1.11	0.24
6	8.32	0.87	0.97	1.78	0.96

Average of Cell Averages: 7.35
Std Dev Between Cell Averages: 0.55
Repeatability Std Dev: 0.91
Reproducibility Std Dev: 0.98

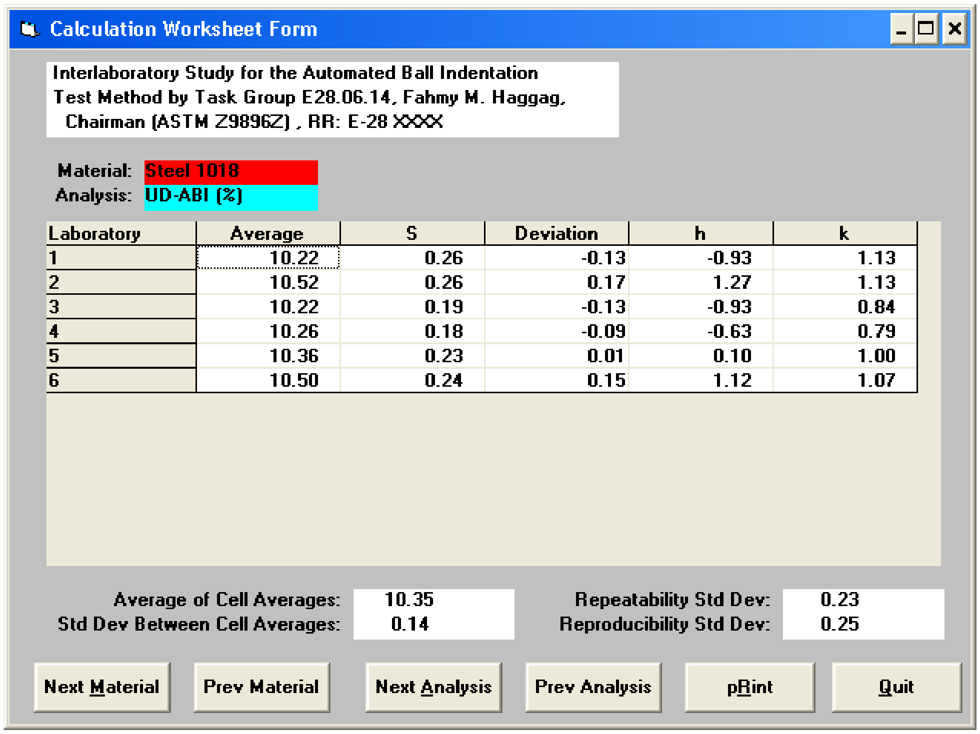


Interlaboratory Study for the Automated Ball Indentation
Test Method by Task Group E28.06.14, Fahmy M. Haggag,
Chairman (ASTM Z9896Z) , RR: E-28 XXXX

Material: Al 7075-T651
Analysis: UD-ABI (%)

Laboratory	Average	S	Deviation	h	k
1	5.34	0.09	-0.46	-0.90	0.13
2	5.72	0.30	-0.08	-0.16	0.44
3	6.74 k	1.57 k	0.94	1.85 k	2.29 k
4	5.38	0.22	-0.42	-0.83	0.32
5	5.72	0.27	-0.08	-0.16	0.39
6	5.90	0.35	0.10	0.20	0.52

Average of Cell Averages: 5.80
Std Dev Between Cell Averages: 0.51
Repeatability Std Dev: 0.68
Reproducibility Std Dev: 0.79

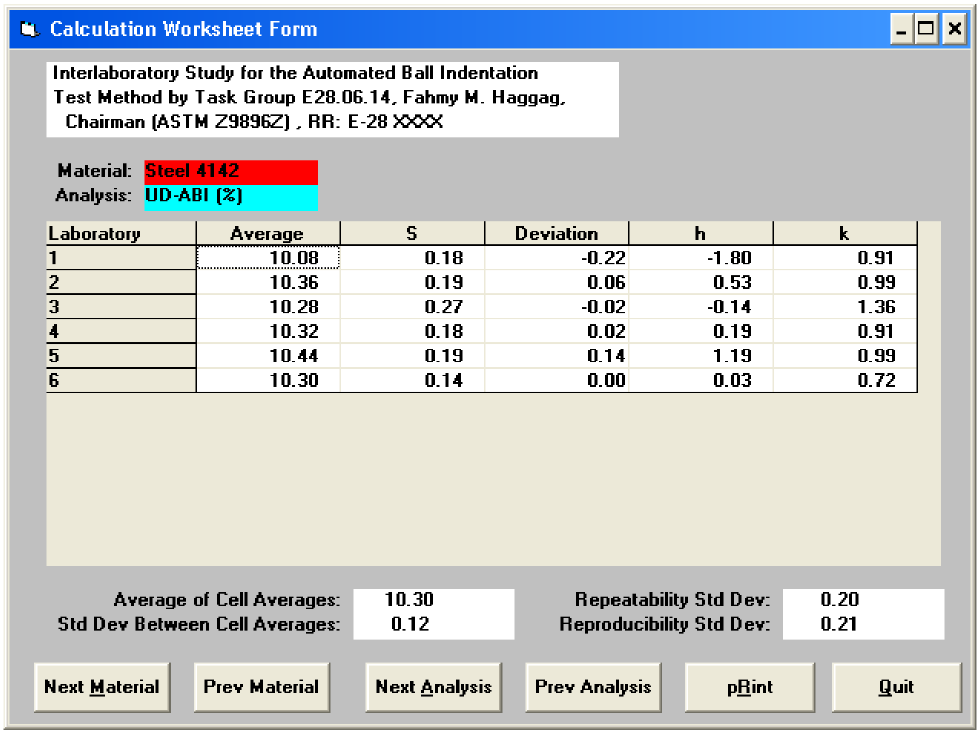


Interlaboratory Study for the Automated Ball Indentation
Test Method by Task Group E28.06.14, Fahmy M. Haggag,
Chairman (ASTM Z9896Z) , RR: E-28 XXXX

Material: Steel 1018
Analysis: UD-ABI (%)

Laboratory	Average	S	Deviation	h	k
1	10.22	0.26	-0.13	-0.93	1.13
2	10.52	0.26	0.17	1.27	1.13
3	10.22	0.19	-0.13	-0.93	0.84
4	10.26	0.18	-0.09	-0.63	0.79
5	10.36	0.23	0.01	0.10	1.00
6	10.50	0.24	0.15	1.12	1.07

Average of Cell Averages: 10.35
Std Dev Between Cell Averages: 0.14
Repeatability Std Dev: 0.23
Reproducibility Std Dev: 0.25



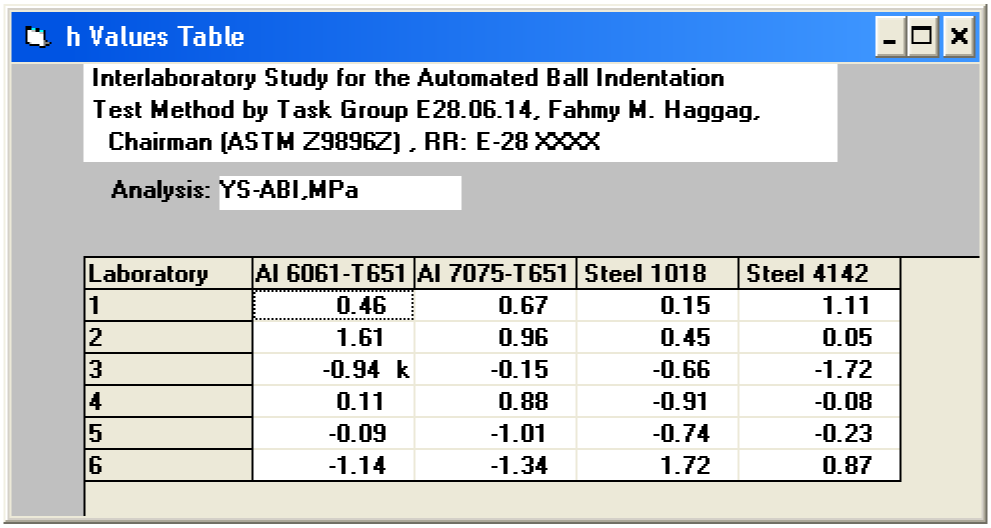
Interlaboratory Study for the Automated Ball Indentation
Test Method by Task Group E28.06.14, Fahmy M. Haggag,
Chairman (ASTM Z9896Z) , RR: E-28 XXXX

Material: Steel 4142
Analysis: UD-ABI (%)

Laboratory	Average	S	Deviation	h	k
1	10.08	0.18	-0.22	-1.80	0.91
2	10.36	0.19	0.06	0.53	0.99
3	10.28	0.27	-0.02	-0.14	1.36
4	10.32	0.18	0.02	0.19	0.91
5	10.44	0.19	0.14	1.19	0.99
6	10.30	0.14	0.00	0.03	0.72

Average of Cell Averages: 10.30
Std Dev Between Cell Averages: 0.12
Repeatability Std Dev: 0.20
Reproducibility Std Dev: 0.21

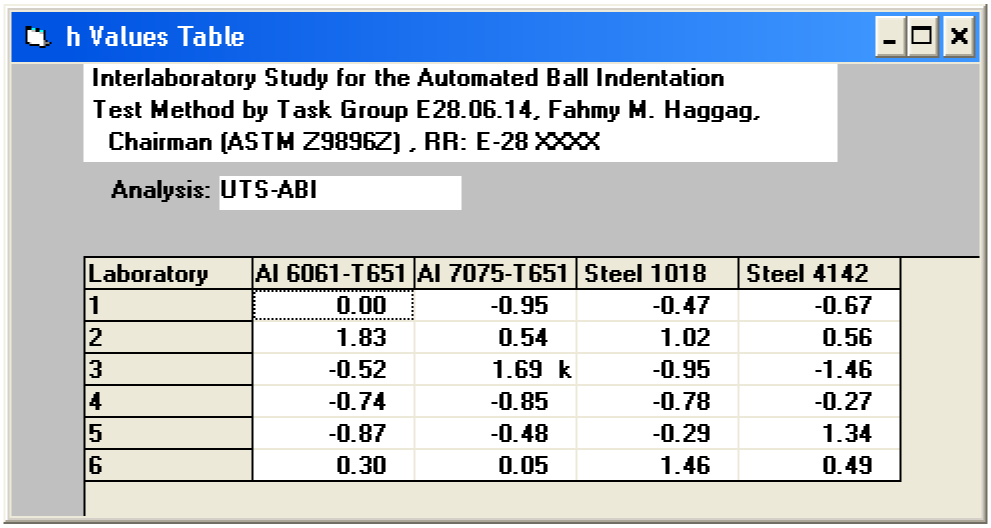
Table 5 – The Between-Laboratory consistency statistic, “h” values by ABI property (analysis)



Interlaboratory Study for the Automated Ball Indentation
Test Method by Task Group E28.06.14, Fahmy M. Haggag,
Chairman (ASTM Z9896Z) , RR: E-28 XXXX

Analysis: YS-ABI,MPa

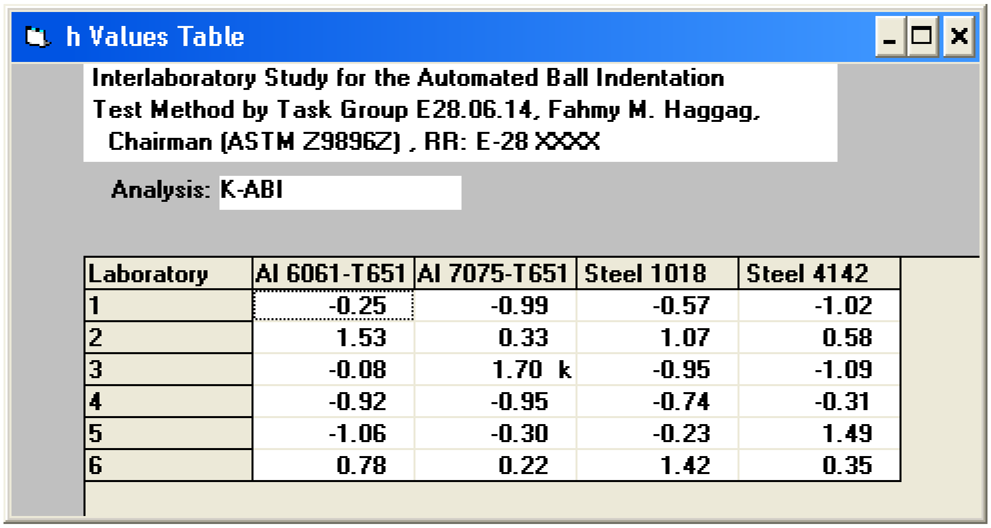
Laboratory	Al 6061-T651	Al 7075-T651	Steel 1018	Steel 4142
1	0.46	0.67	0.15	1.11
2	1.61	0.96	0.45	0.05
3	-0.94 k	-0.15	-0.66	-1.72
4	0.11	0.88	-0.91	-0.08
5	-0.09	-1.01	-0.74	-0.23
6	-1.14	-1.34	1.72	0.87



Interlaboratory Study for the Automated Ball Indentation
Test Method by Task Group E28.06.14, Fahmy M. Haggag,
Chairman (ASTM Z9896Z) , RR: E-28 XXXX

Analysis: UTS-ABI

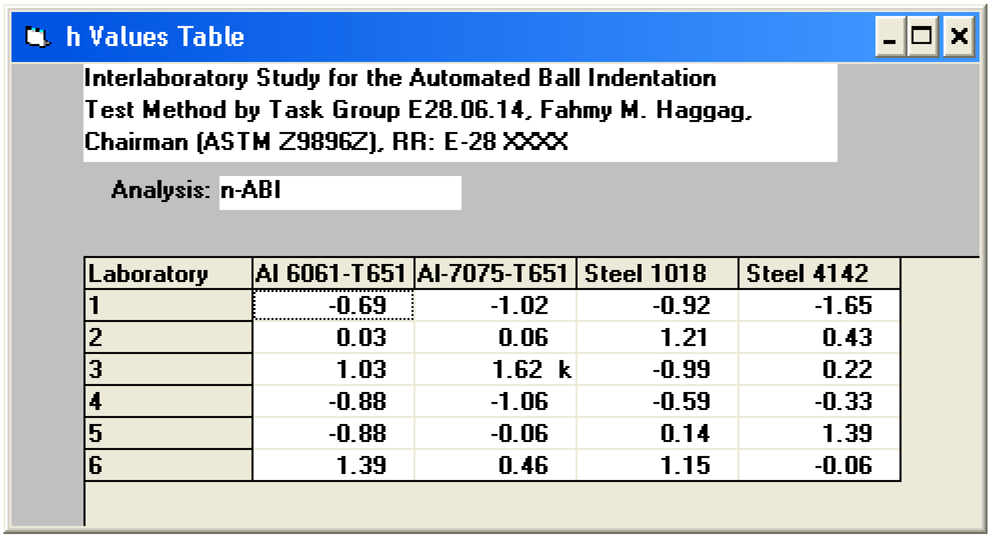
Laboratory	Al 6061-T651	Al 7075-T651	Steel 1018	Steel 4142
1	0.00	-0.95	-0.47	-0.67
2	1.83	0.54	1.02	0.56
3	-0.52	1.69 k	-0.95	-1.46
4	-0.74	-0.85	-0.78	-0.27
5	-0.87	-0.48	-0.29	1.34
6	0.30	0.05	1.46	0.49



Interlaboratory Study for the Automated Ball Indentation
Test Method by Task Group E28.06.14, Fahmy M. Haggag,
Chairman (ASTM Z9896Z) , RR: E-28 XXXX

Analysis: K-ABI

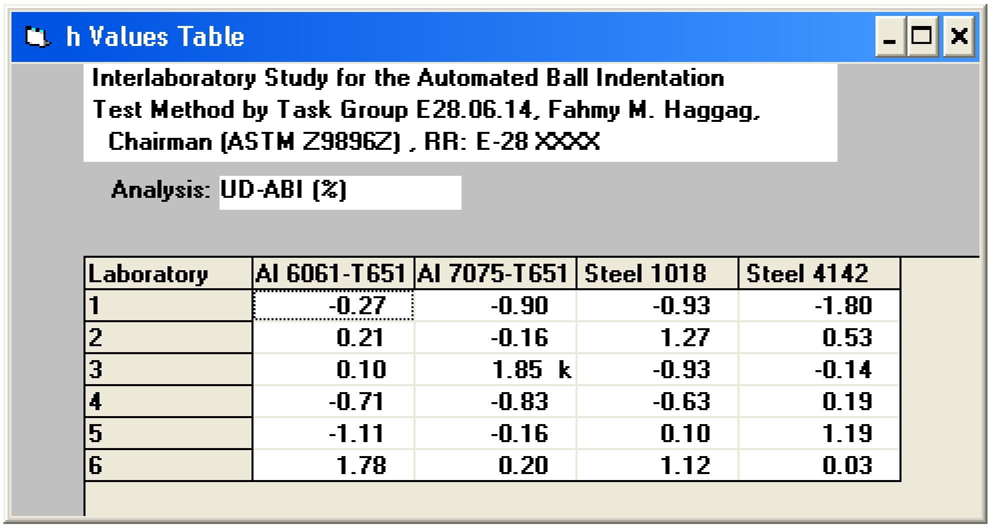
Laboratory	Al 6061-T651	Al 7075-T651	Steel 1018	Steel 4142
1	-0.25	-0.99	-0.57	-1.02
2	1.53	0.33	1.07	0.58
3	-0.08	1.70 k	-0.95	-1.09
4	-0.92	-0.95	-0.74	-0.31
5	-1.06	-0.30	-0.23	1.49
6	0.78	0.22	1.42	0.35



Interlaboratory Study for the Automated Ball Indentation
Test Method by Task Group E28.06.14, Fahmy M. Haggag,
Chairman (ASTM Z9896Z), RR: E-28 XXXX

Analysis: n-ABI

Laboratory	Al 6061-T651	Al-7075-T651	Steel 1018	Steel 4142
1	-0.69	-1.02	-0.92	-1.65
2	0.03	0.06	1.21	0.43
3	1.03	1.62 k	-0.99	0.22
4	-0.88	-1.06	-0.59	-0.33
5	-0.88	-0.06	0.14	1.39
6	1.39	0.46	1.15	-0.06

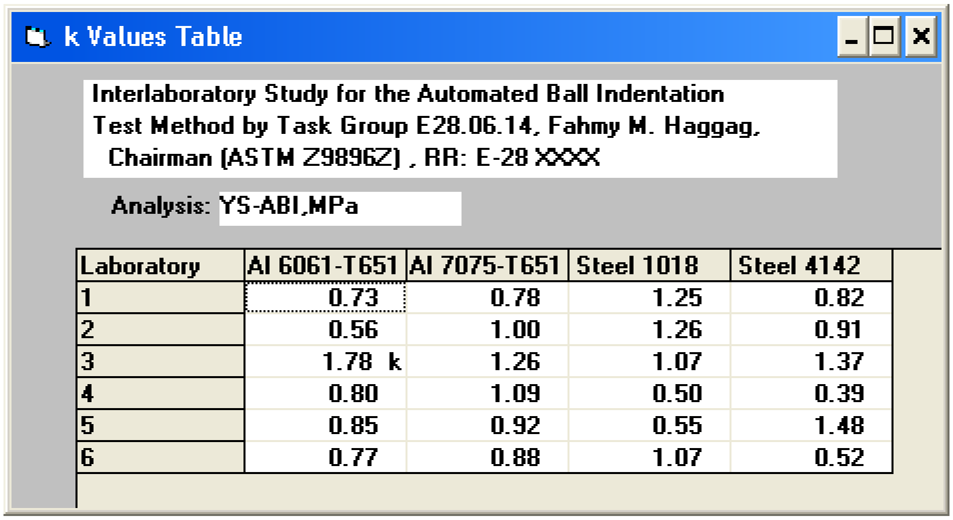


Interlaboratory Study for the Automated Ball Indentation
Test Method by Task Group E28.06.14, Fahmy M. Haggag,
Chairman (ASTM Z9896Z) , RR: E-28 XXXX

Analysis: UD-ABI (%)

Laboratory	Al 6061-T651	Al 7075-T651	Steel 1018	Steel 4142
1	-0.27	-0.90	-0.93	-1.80
2	0.21	-0.16	1.27	0.53
3	0.10	1.85 k	-0.93	-0.14
4	-0.71	-0.83	-0.63	0.19
5	-1.11	-0.16	0.10	1.19
6	1.78	0.20	1.12	0.03

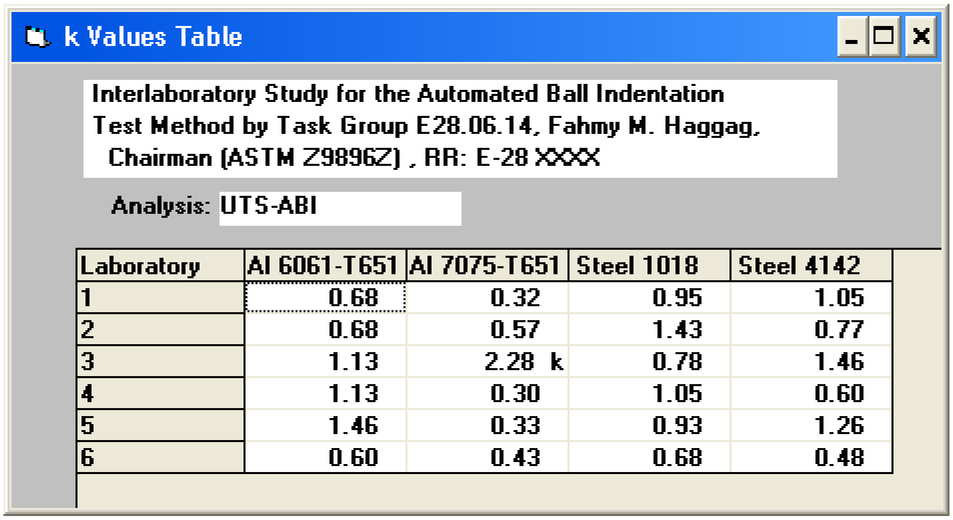
Table 6 – The Within-Laboratory consistency statistic, “k” values by ABI property (analysis)



Interlaboratory Study for the Automated Ball Indentation
Test Method by Task Group E28.06.14, Fahmy M. Haggag,
Chairman (ASTM Z9896Z) , RR: E-28 XXXX

Analysis: YS-ABI,MPa

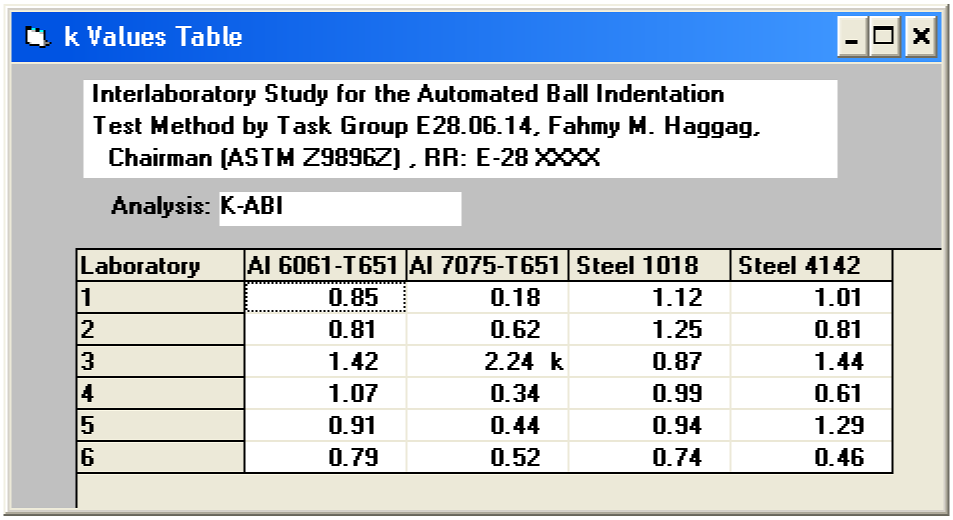
Laboratory	Al 6061-T651	Al 7075-T651	Steel 1018	Steel 4142
1	0.73	0.78	1.25	0.82
2	0.56	1.00	1.26	0.91
3	1.78 k	1.26	1.07	1.37
4	0.80	1.09	0.50	0.39
5	0.85	0.92	0.55	1.48
6	0.77	0.88	1.07	0.52



Interlaboratory Study for the Automated Ball Indentation
Test Method by Task Group E28.06.14, Fahmy M. Haggag,
Chairman (ASTM Z9896Z) , RR: E-28 XXXX

Analysis: UTS-ABI

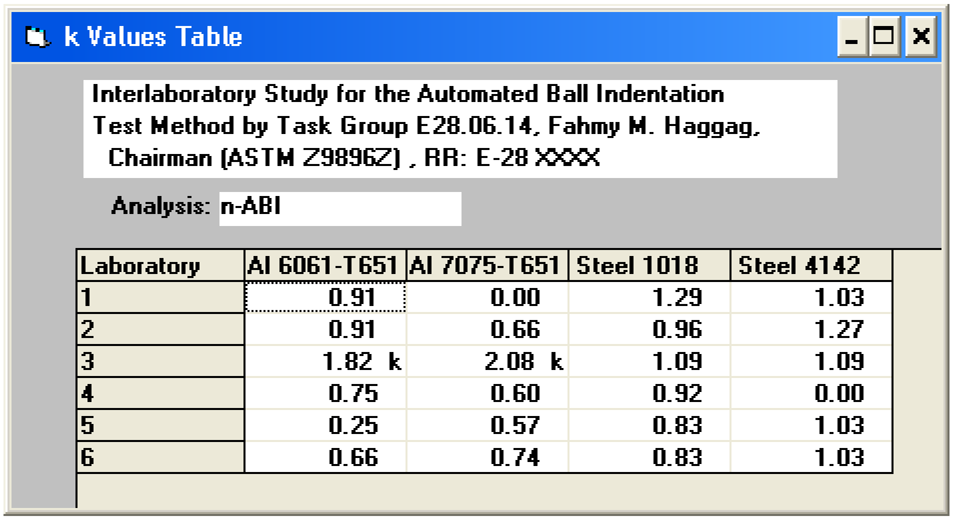
Laboratory	Al 6061-T651	Al 7075-T651	Steel 1018	Steel 4142
1	0.68	0.32	0.95	1.05
2	0.68	0.57	1.43	0.77
3	1.13	2.28 k	0.78	1.46
4	1.13	0.30	1.05	0.60
5	1.46	0.33	0.93	1.26
6	0.60	0.43	0.68	0.48



Interlaboratory Study for the Automated Ball Indentation
Test Method by Task Group E28.06.14, Fahmy M. Haggag,
Chairman (ASTM Z9896Z) , RR: E-28 XXXX

Analysis: K-ABI

Laboratory	Al 6061-T651	Al 7075-T651	Steel 1018	Steel 4142
1	0.85	0.18	1.12	1.01
2	0.81	0.62	1.25	0.81
3	1.42	2.24 k	0.87	1.44
4	1.07	0.34	0.99	0.61
5	0.91	0.44	0.94	1.29
6	0.79	0.52	0.74	0.46

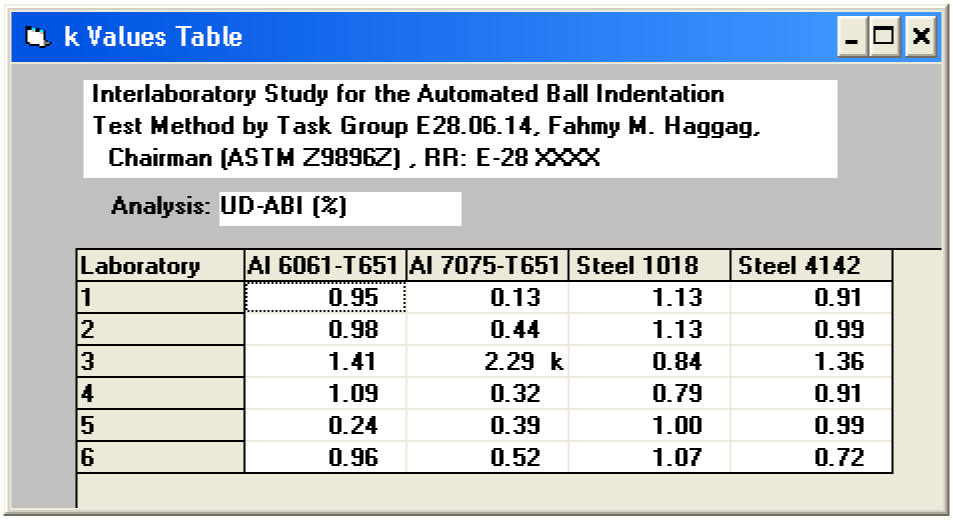


k Values Table

Interlaboratory Study for the Automated Ball Indentation
Test Method by Task Group E28.06.14, Fahmy M. Haggag,
Chairman (ASTM Z9896Z) , RR: E-28 XXXX

Analysis: n-ABI

Laboratory	Al 6061-T651	Al 7075-T651	Steel 1018	Steel 4142
1	0.91	0.00	1.29	1.03
2	0.91	0.66	0.96	1.27
3	1.82 k	2.08 k	1.09	1.09
4	0.75	0.60	0.92	0.00
5	0.25	0.57	0.83	1.03
6	0.66	0.74	0.83	1.03



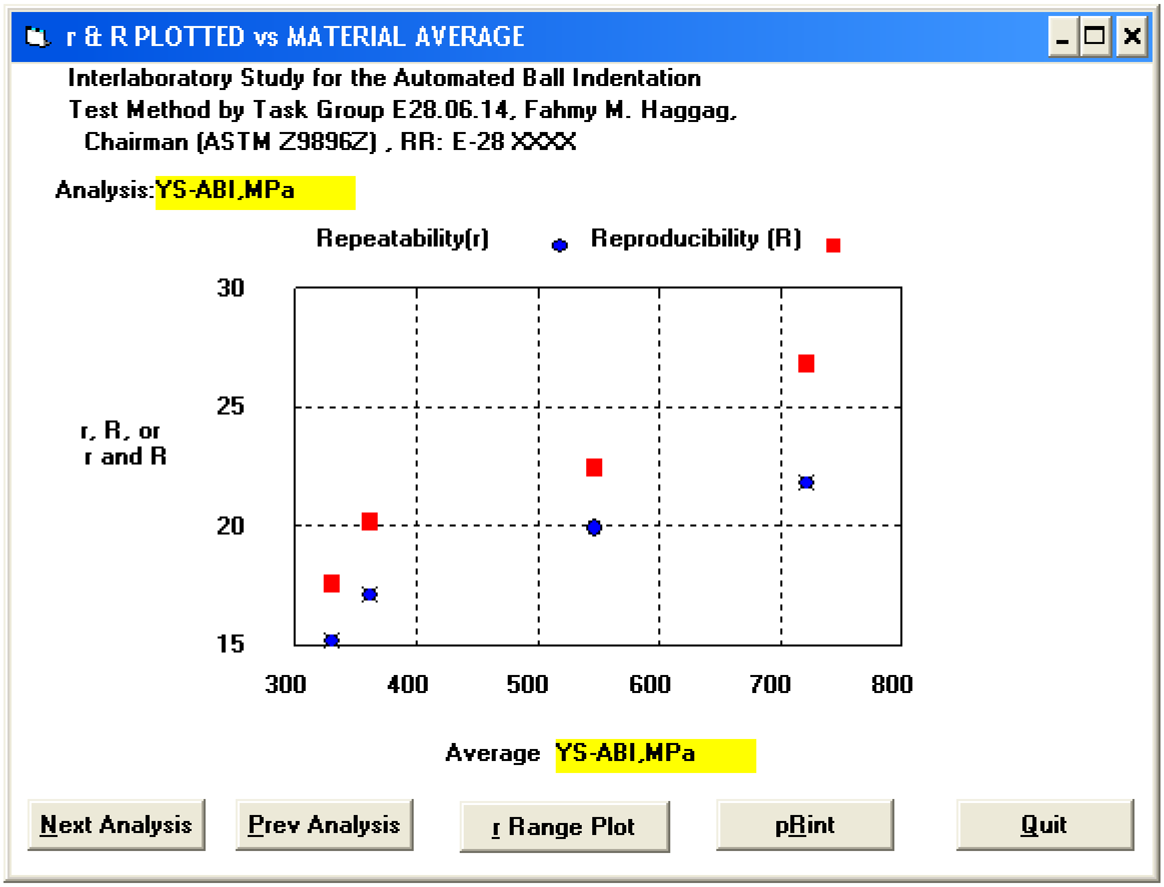
k Values Table

Interlaboratory Study for the Automated Ball Indentation
Test Method by Task Group E28.06.14, Fahmy M. Haggag,
Chairman (ASTM Z9896Z) , RR: E-28 XXXX

Analysis: UD-ABI (%)

Laboratory	Al 6061-T651	Al 7075-T651	Steel 1018	Steel 4142
1	0.95	0.13	1.13	0.91
2	0.98	0.44	1.13	0.99
3	1.41	2.29 k	0.84	1.36
4	1.09	0.32	0.79	0.91
5	0.24	0.39	1.00	0.99
6	0.96	0.52	1.07	0.72

Fig. 1A Within- and Between-Laboratory Repeatability (r and R) for the YS-ABI, MPa

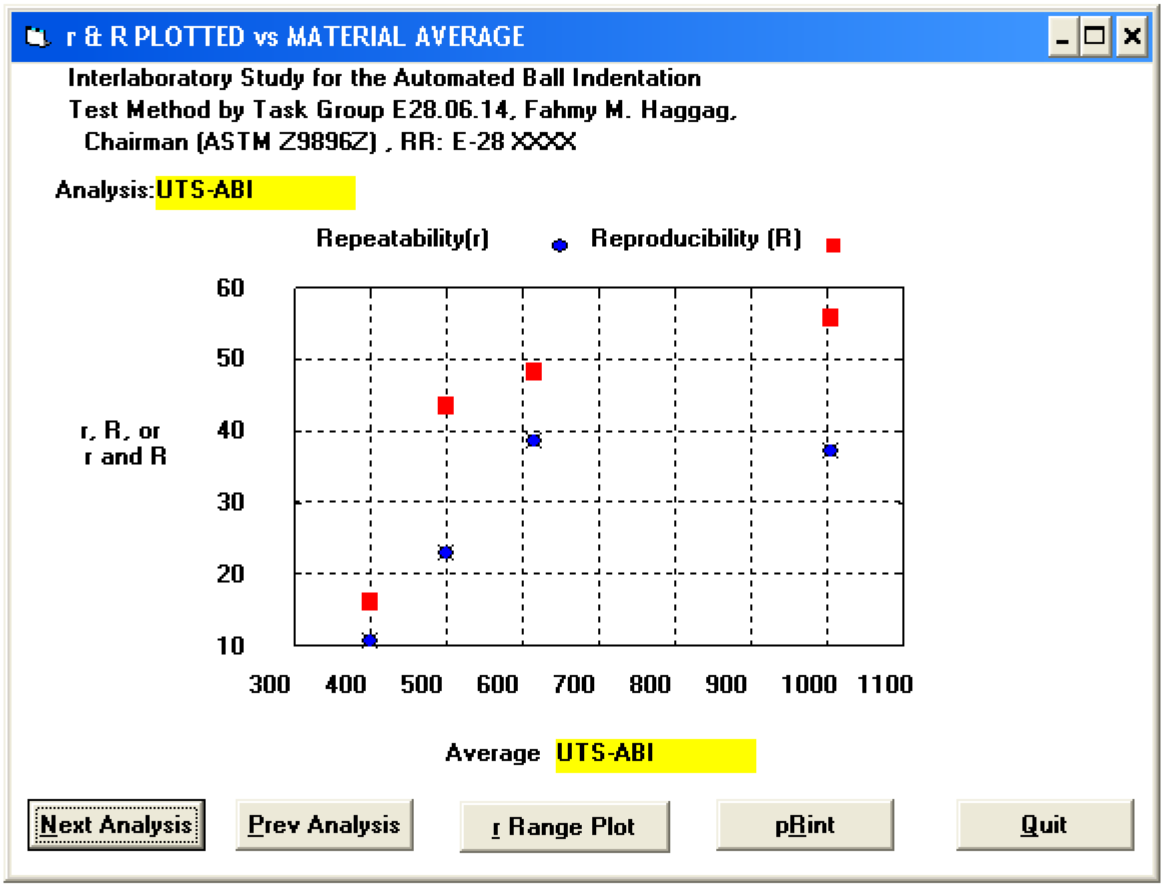


Interlaboratory Study for the Automated Ball Indentation
Test Method by Task Group E28.06.14, Fahmy M. Haggag,
Chairman (ASTM Z9896Z) , RR: E-28 XXXX

Analysis: YS-ABI,MPa

Average YS-ABI,MPa

Fig. 1B Within- and Between-Laboratory Repeatability (r and R) for the UTS-ABI, MPa



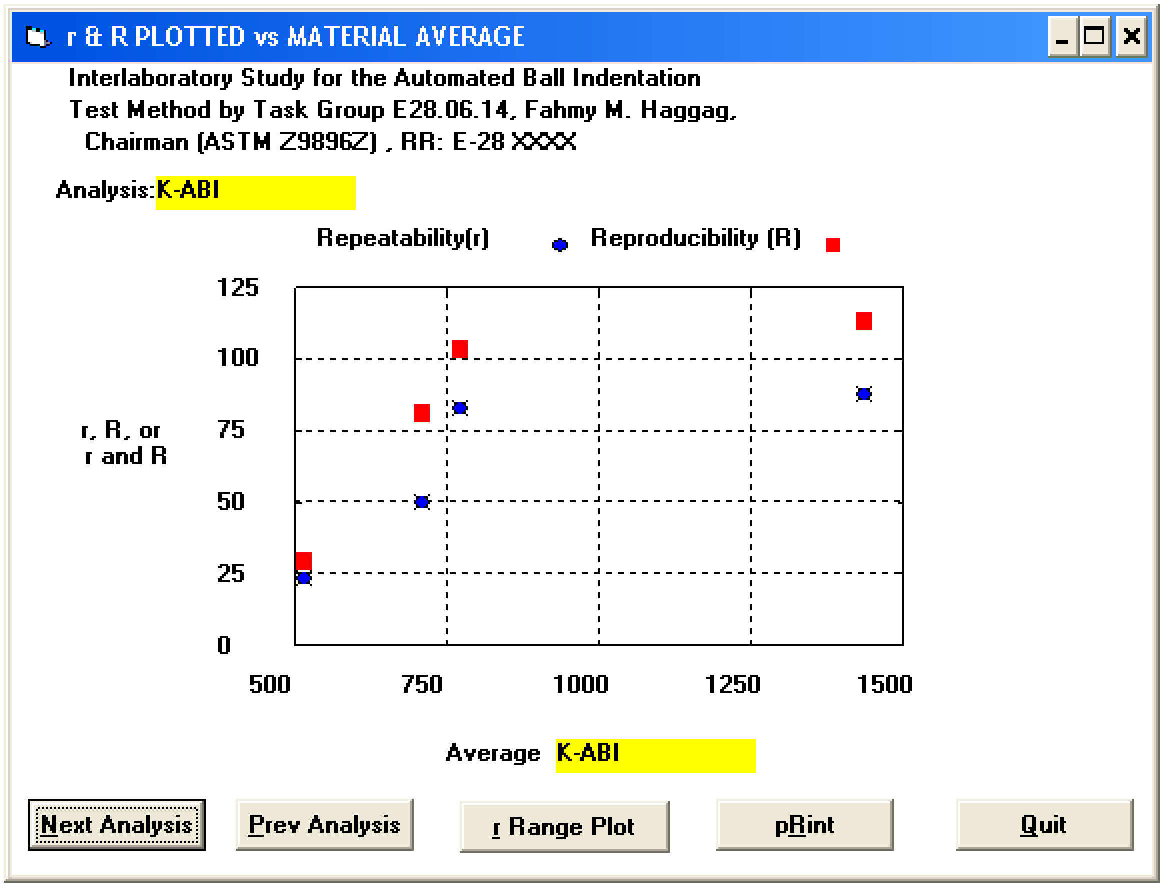
r & R PLOTTED vs MATERIAL AVERAGE

Interlaboratory Study for the Automated Ball Indentation
Test Method by Task Group E28.06.14, Fahmy M. Haggag,
Chairman (ASTM Z9896Z) , RR: E-28 XXXX

Analysis: UTS-ABI

Average UTS-ABI

Fig. 1C Within- and Between-Laboratory Repeatability (r and R) for the K-ABI, MPa



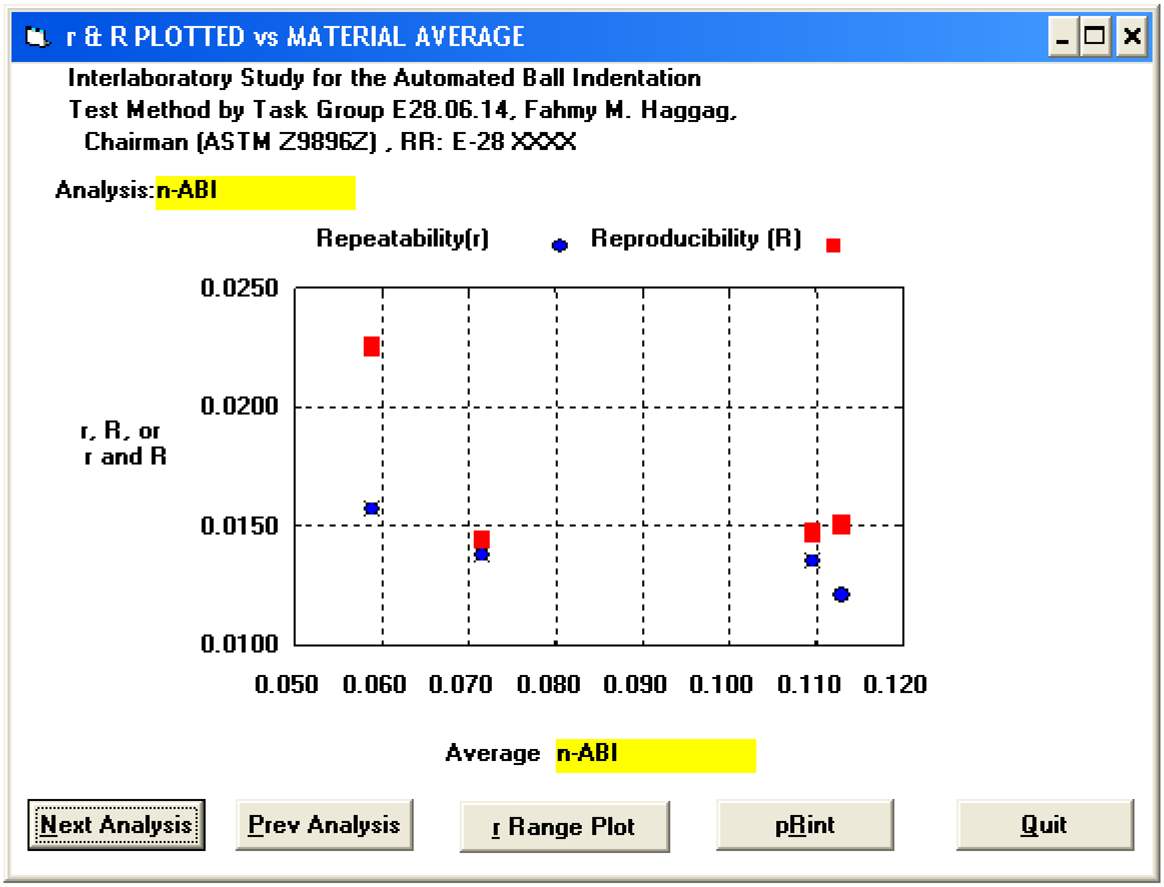
r & R PLOTTED vs MATERIAL AVERAGE

Interlaboratory Study for the Automated Ball Indentation
Test Method by Task Group E28.06.14, Fahmy M. Haggag,
Chairman (ASTM Z9896Z) , RR: E-28 XXXX

Analysis: K-ABI

Average K-ABI

Fig. 1D Within- and Between-Laboratory Repeatability (r and R) for the n-ABI

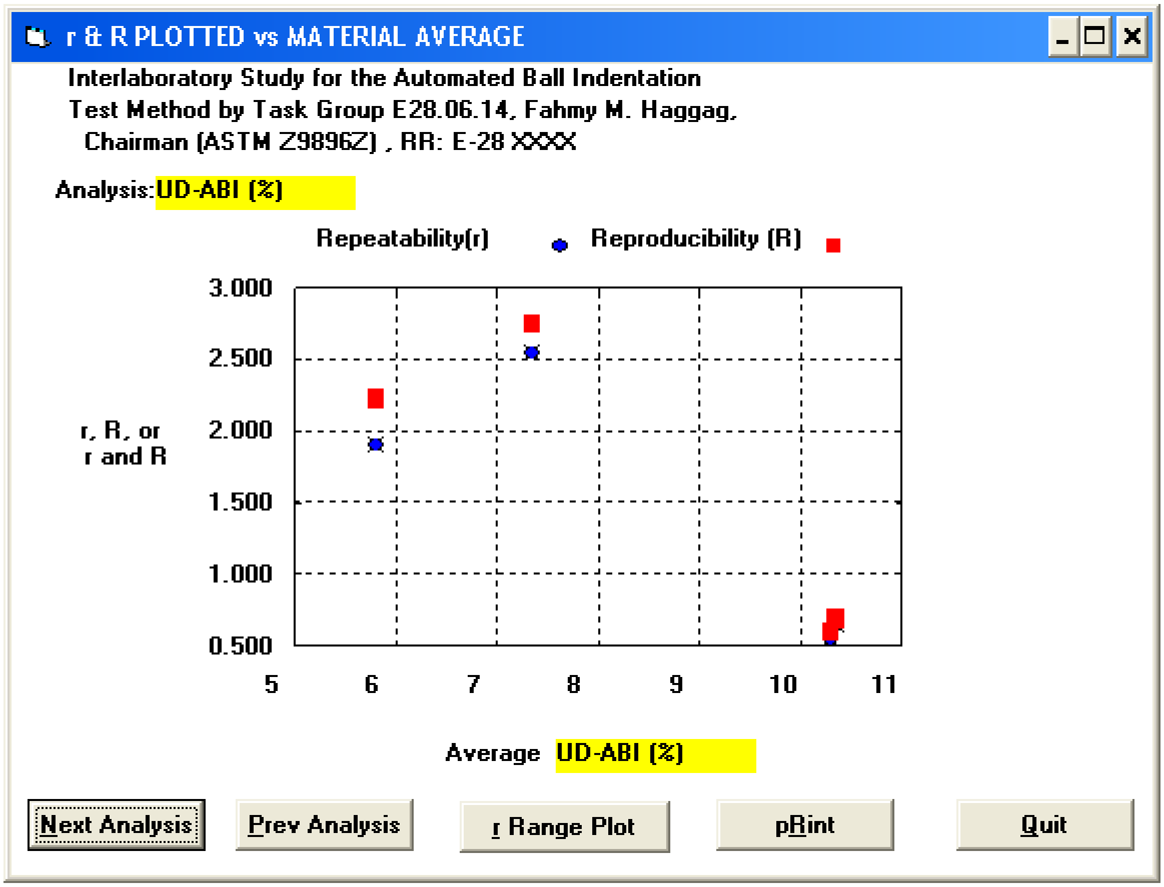


Interlaboratory Study for the Automated Ball Indentation
Test Method by Task Group E28.06.14, Fahmy M. Haggag,
Chairman (ASTM Z9896Z) , RR: E-28 XXXX

Analysis: n-ABI

Average n-ABI

Fig. 1E Within- and Between-Laboratory Repeatability (r and R) for the UD-ABI, Percent



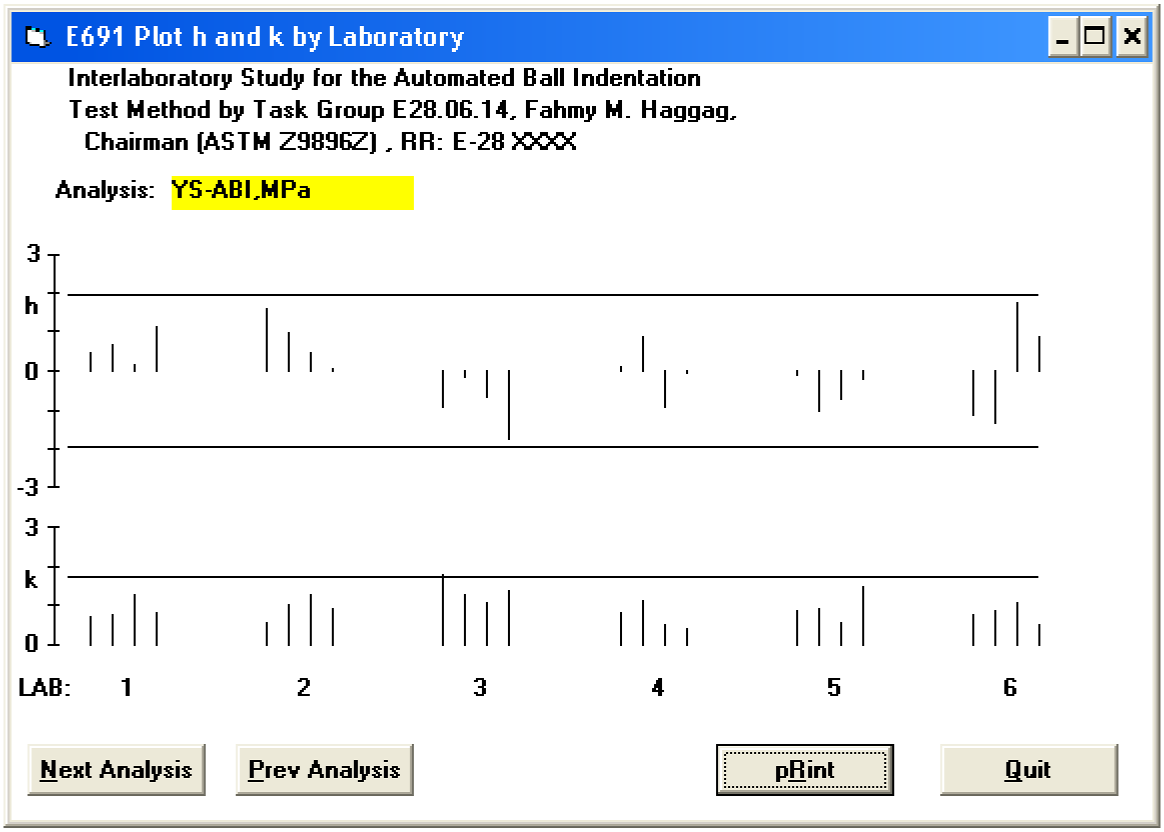
r & R PLOTTED vs MATERIAL AVERAGE

Interlaboratory Study for the Automated Ball Indentation
Test Method by Task Group E28.06.14, Fahmy M. Haggag,
Chairman (ASTM Z9896Z) , RR: E-28 XXXX

Analysis: UD-ABI (%)

Average UD-ABI (%)

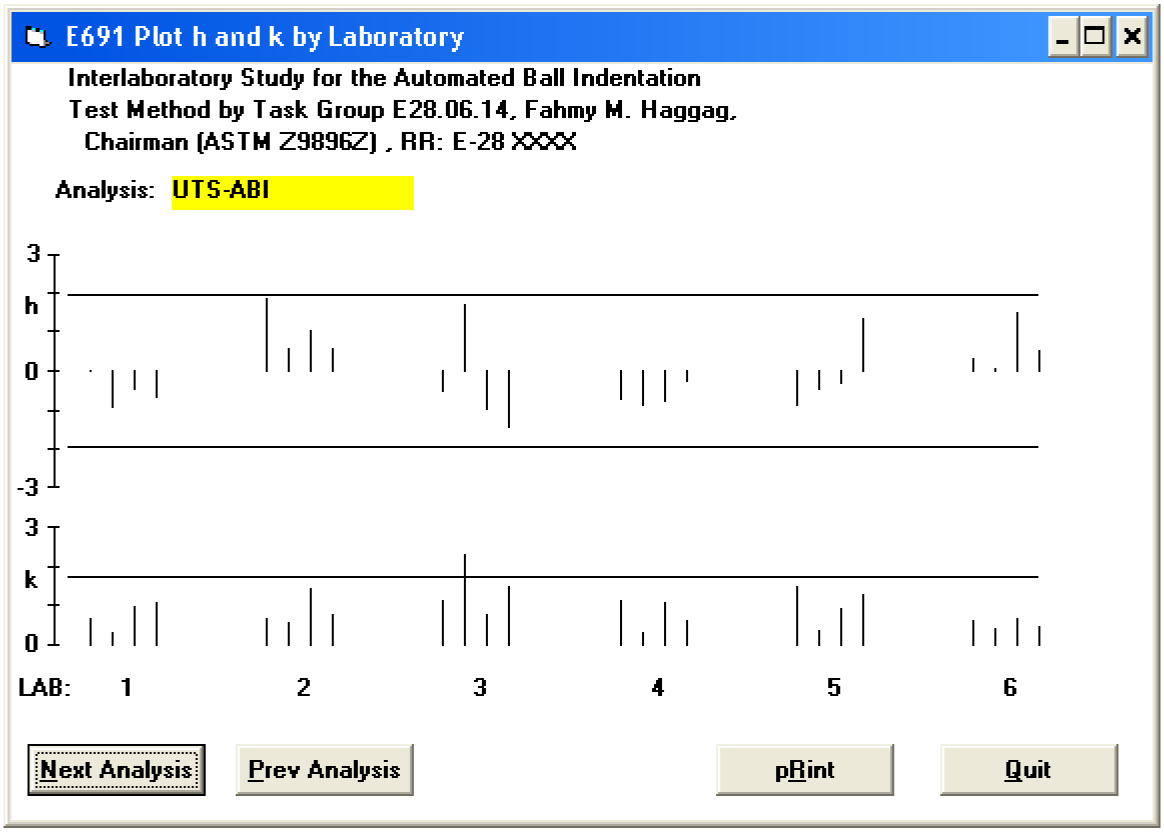
Fig. 2A Consistency statistic plots of the h and k values by laboratory for the YS-ABI, MPa



Interlaboratory Study for the Automated Ball Indentation
Test Method by Task Group E28.06.14, Fahmy M. Haggag,
Chairman (ASTM Z9896Z) , RR: E-28 XXXX

Analysis: YS-ABI,MPa

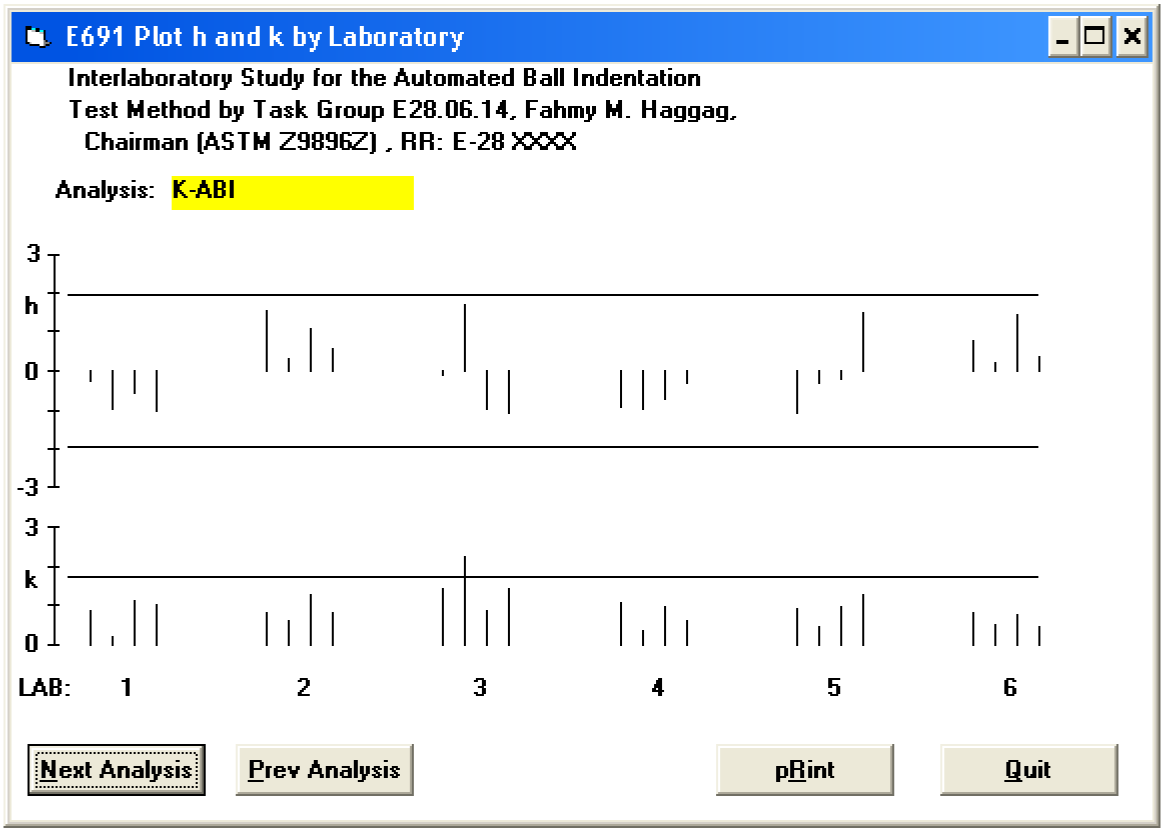
Fig. 2B **Consistency statistic plots of the h and k values by laboratory for the UTS-ABI, MPa**



Interlaboratory Study for the Automated Ball Indentation
Test Method by Task Group E28.06.14, Fahmy M. Haggag,
Chairman (ASTM Z9896Z) , RR: E-28 XXXX

Analysis: UTS-ABI

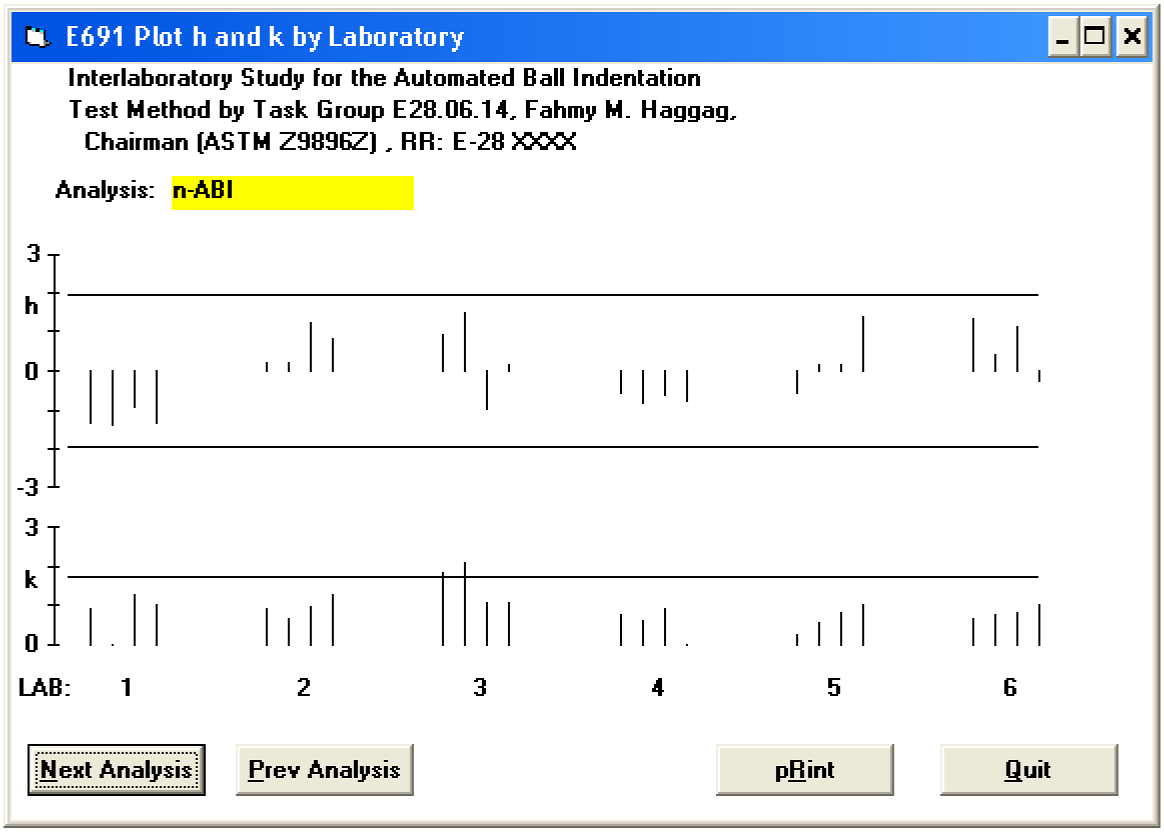
Fig. 2C Consistency statistic plots of the h and k values by laboratory for the K-ABI, MPa



Interlaboratory Study for the Automated Ball Indentation
Test Method by Task Group E28.06.14, Fahmy M. Haggag,
Chairman (ASTM Z9896Z) , RR: E-28 XXXX

Analysis: K-ABI

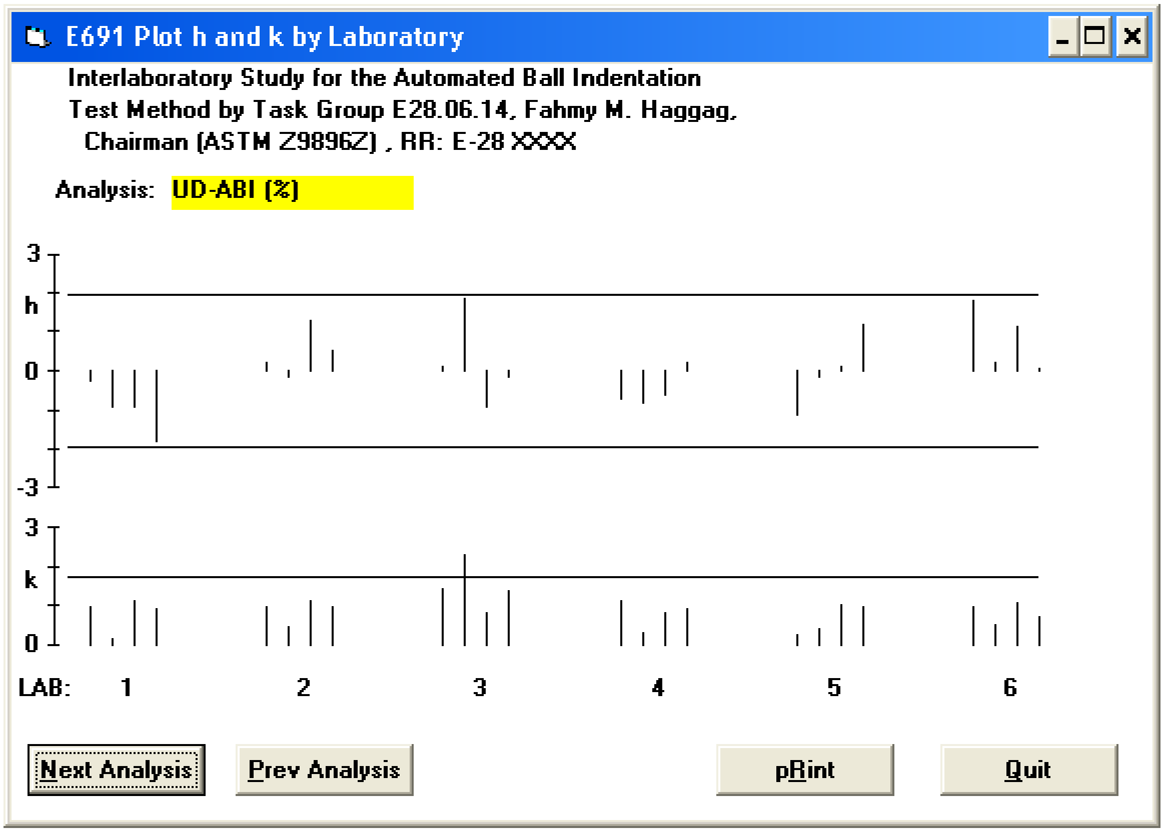
Fig. 2D Consistency statistic plots of the h and k values by laboratory for the n-ABI



Interlaboratory Study for the Automated Ball Indentation
Test Method by Task Group E28.06.14, Fahmy M. Haggag,
Chairman (ASTM Z9896Z) , RR: E-28 XXXX

Analysis: n-ABI

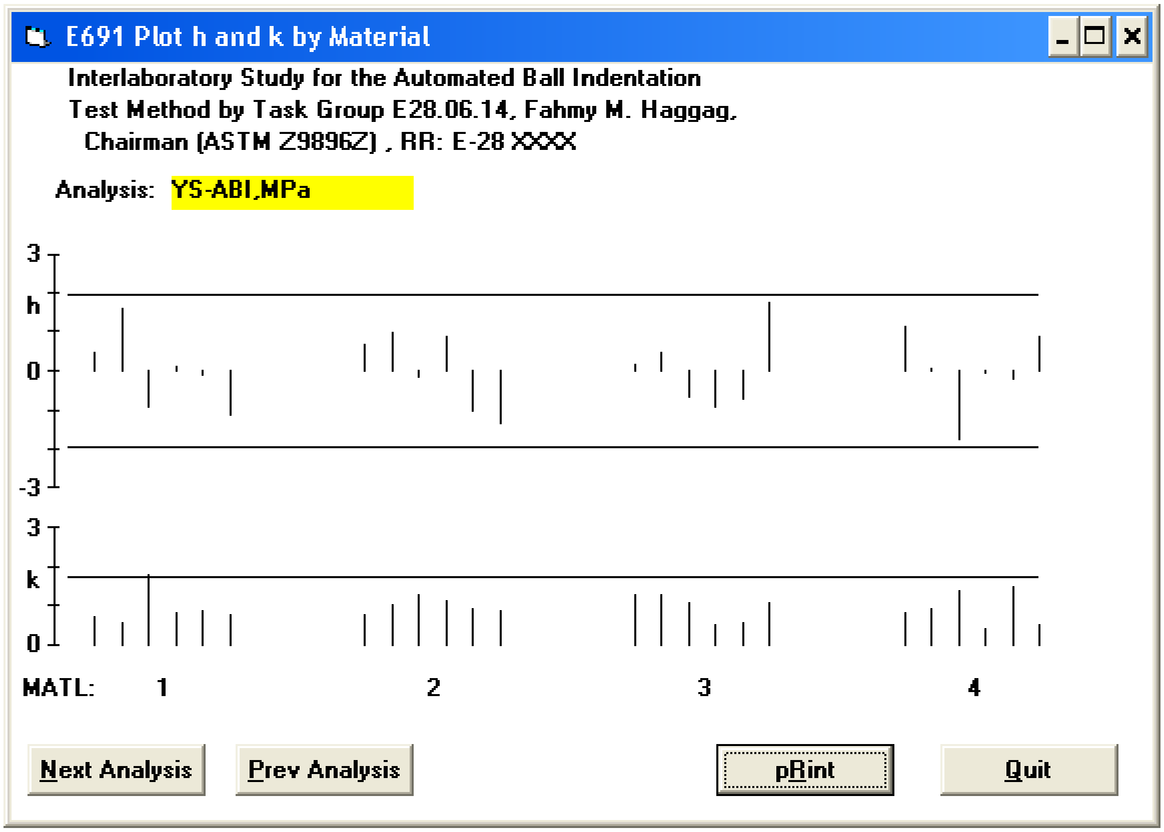
Fig. 2E Consistency statistic plots of the h and k values by laboratory for the UD-ABI, Percent



Interlaboratory Study for the Automated Ball Indentation
Test Method by Task Group E28.06.14, Fahmy M. Haggag,
Chairman (ASTM Z9896Z) , RR: E-28 XXXX

Analysis: UD-ABI (%)

Fig. 3A Consistency statistic plots of the h and k values by material for the YS-ABI, MPa



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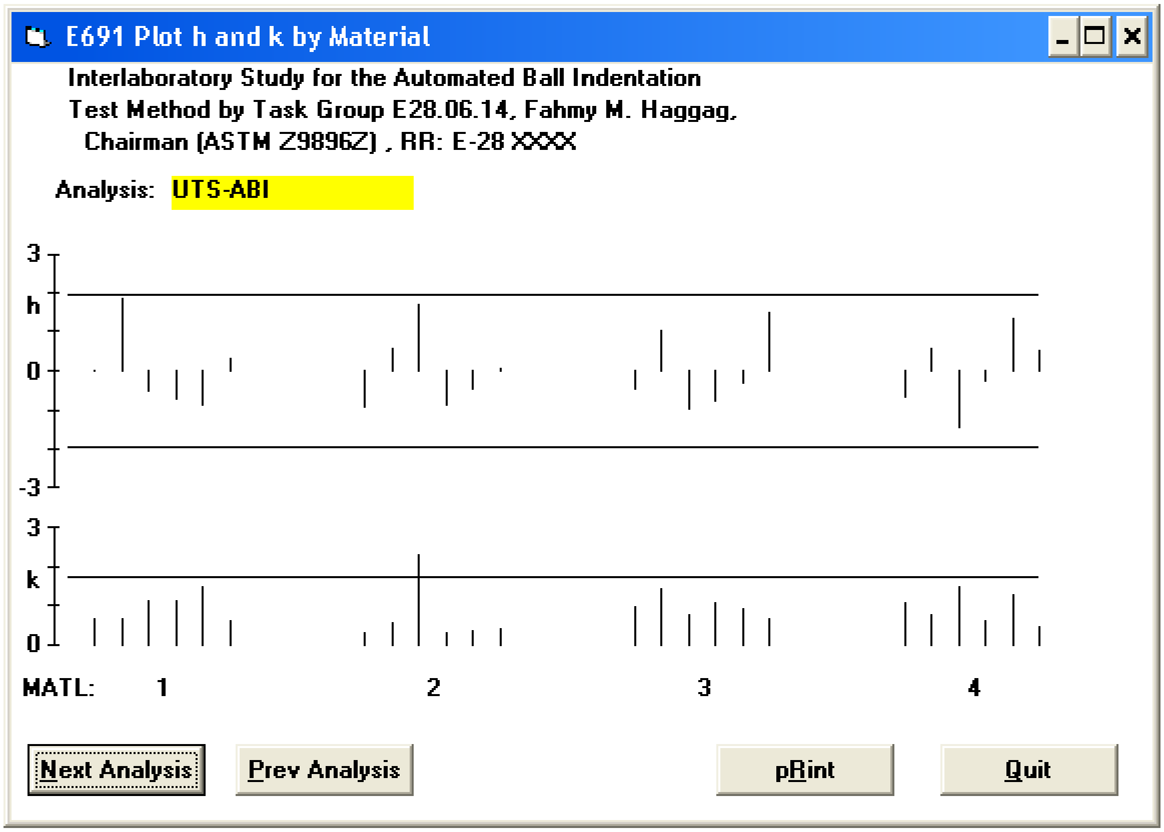
Chairman (ASTM Z9896Z) , RR: E-28 XXXX

Analysis: YS-ABI,MPa

Fig. 3B Consistency statistic plots of the h and k values by material for the UTS-ABI, MPa



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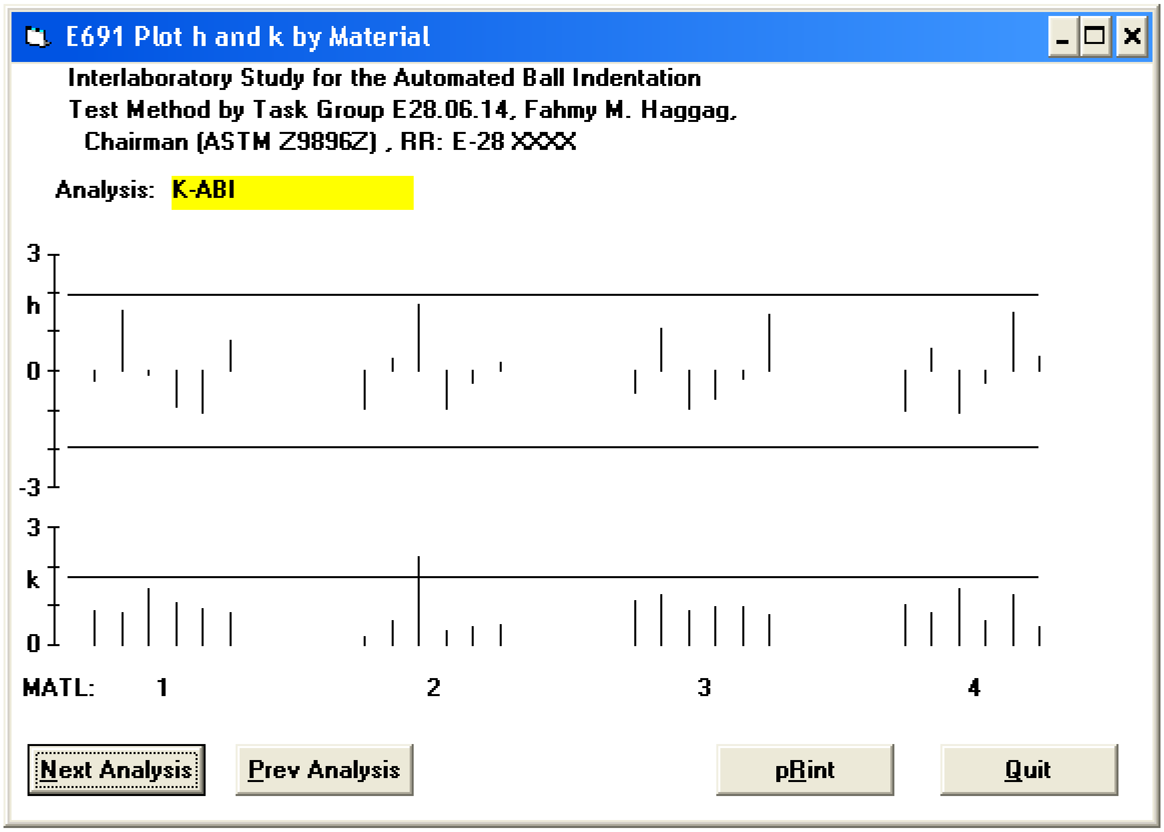
Chairman (ASTM Z9896Z) , RR: E-28 XXXX

Analysis: UTS-ABI

Fig. 3C Consistency statistic plots of the h and k values by material for the K-ABI, MPa



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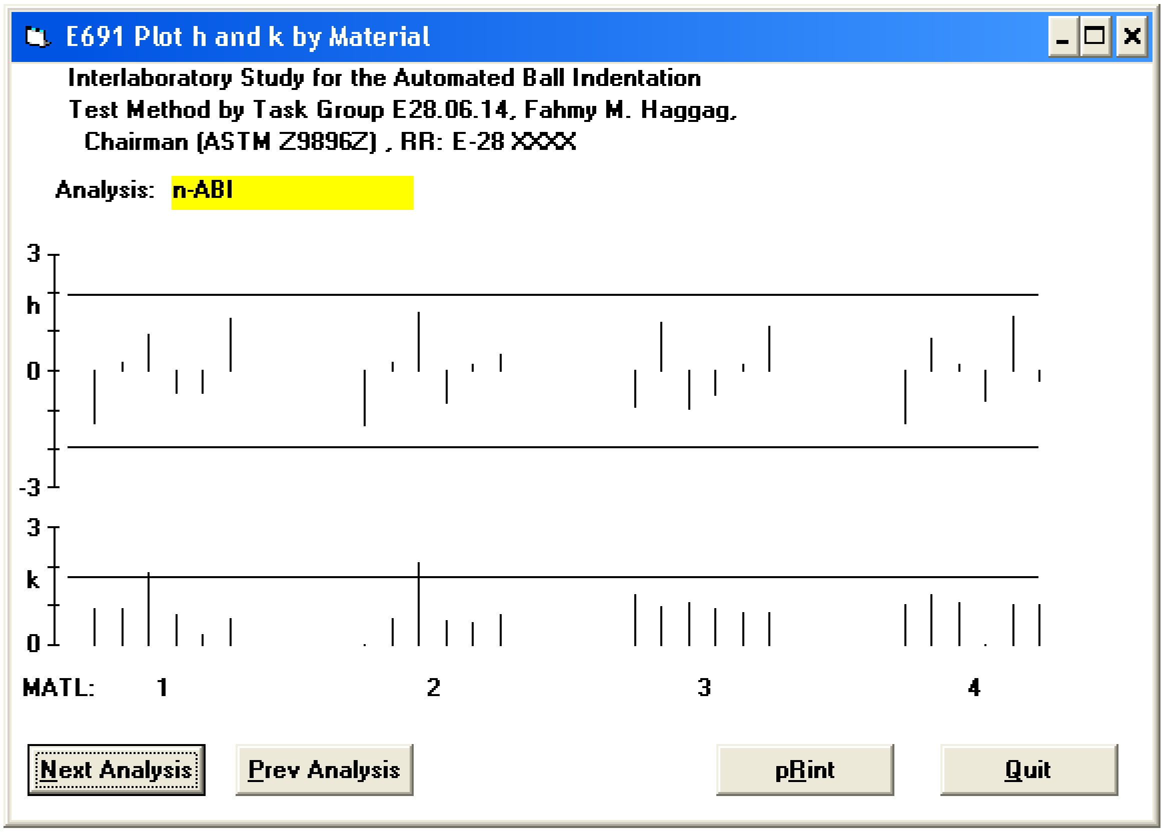
Chairman (ASTM Z9896Z) , RR: E-28 XXXX

Analysis: K-ABI

Fig. 3D Consistency statistic plots of the h and k values by material for the n-ABI



E691 Plot h and k by Material

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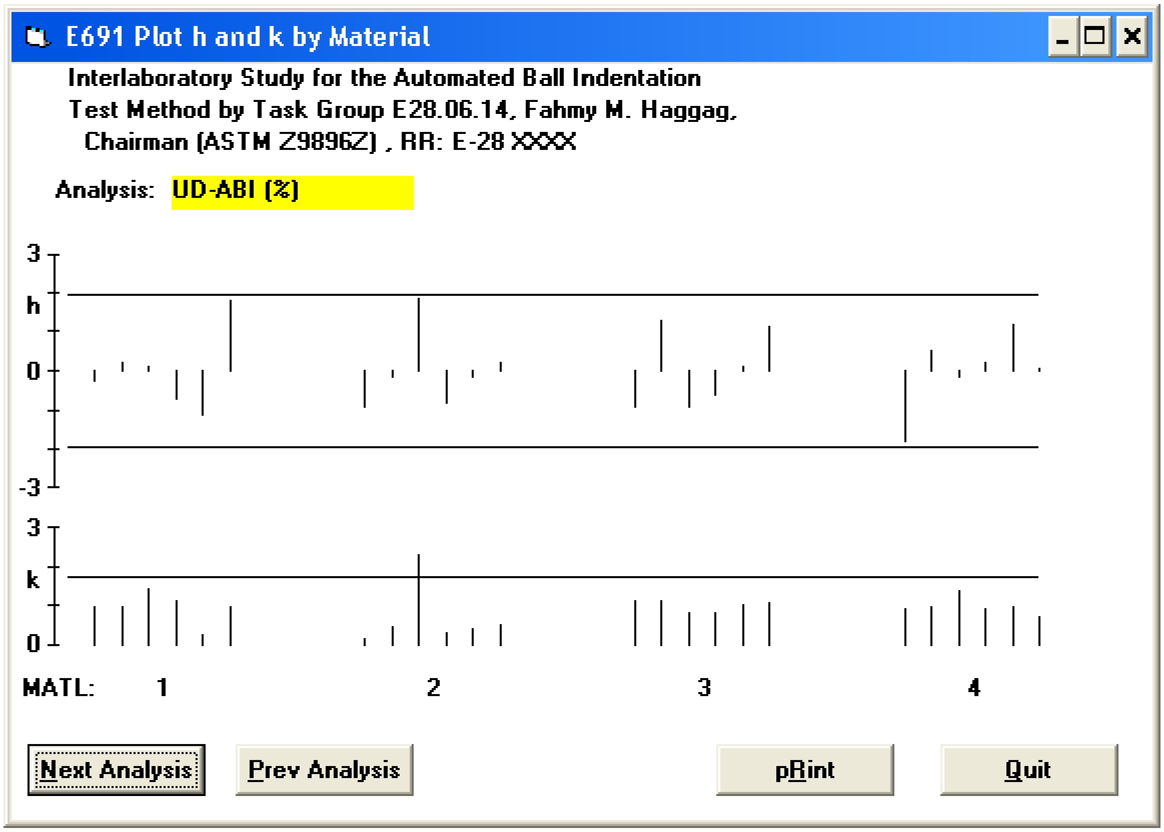
Analysis: n-ABI

Fig. 3E Consistency statistic plots of the h and k values by material for the UD-ABI, Percent



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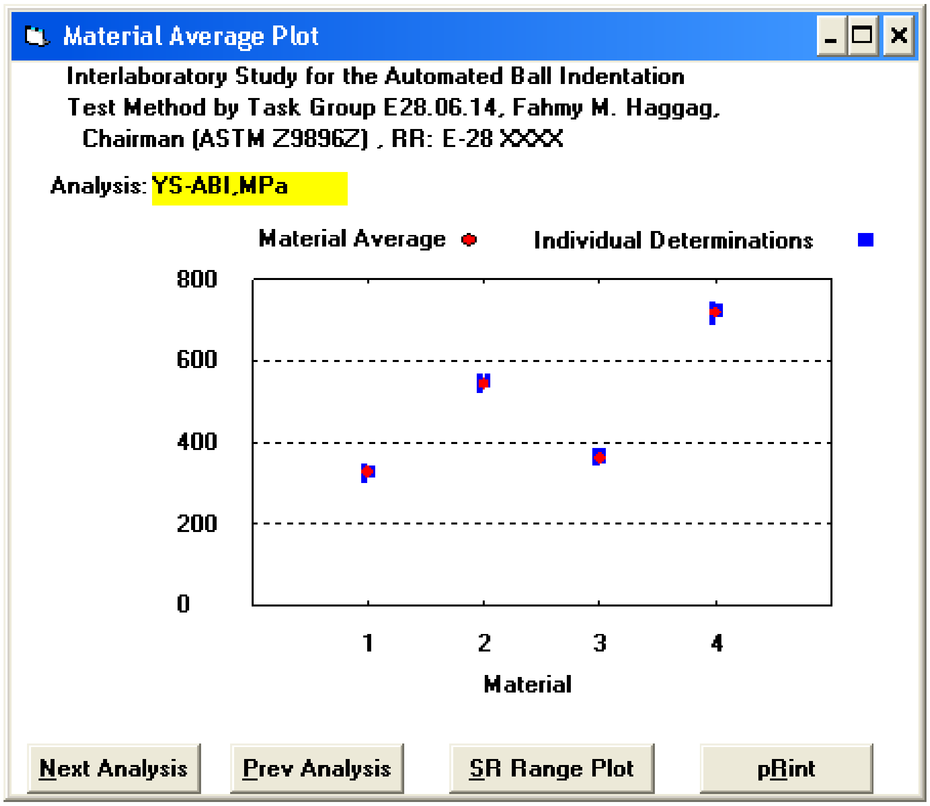
Chairman (ASTM Z9896Z) , RR: E-28 XXXX

Analysis: UD-ABI (%)

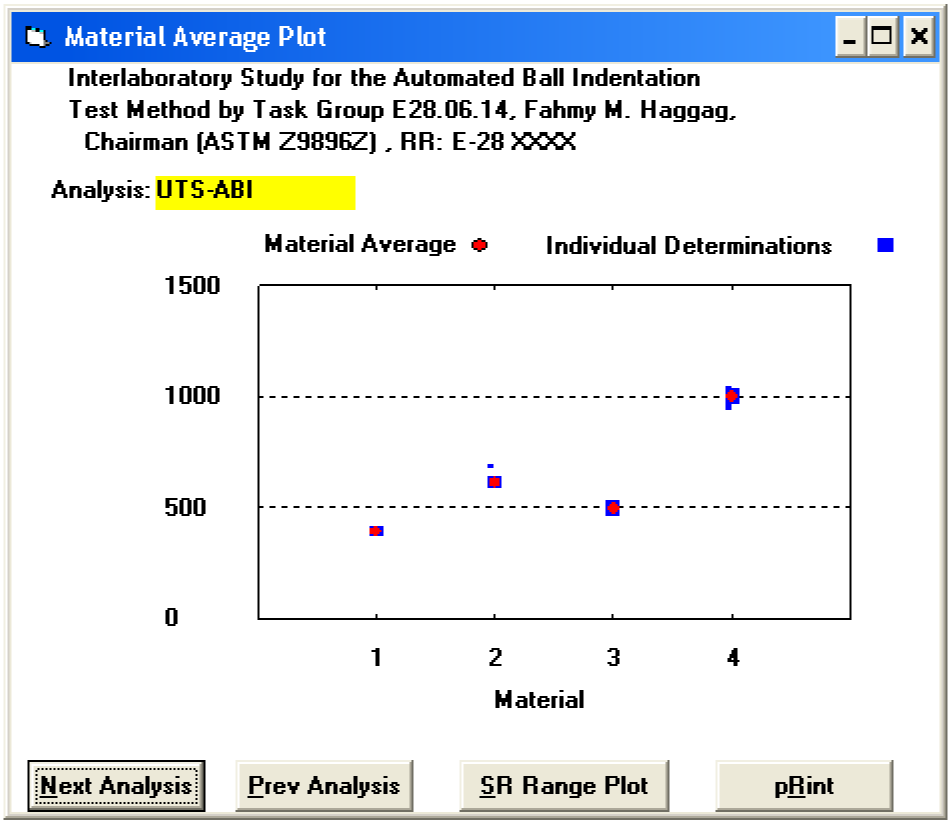
Fig. 4A Plot of the individual and average values of the YS-ABI, MPa



Interlaboratory Study for the Automated Ball Indentation
Test Method by Task Group E28.06.14, Fahmy M. Haggag,
Chairman (ASTM Z9896Z) , RR: E-28 XXXX

Analysis: YS-ABI,MPa

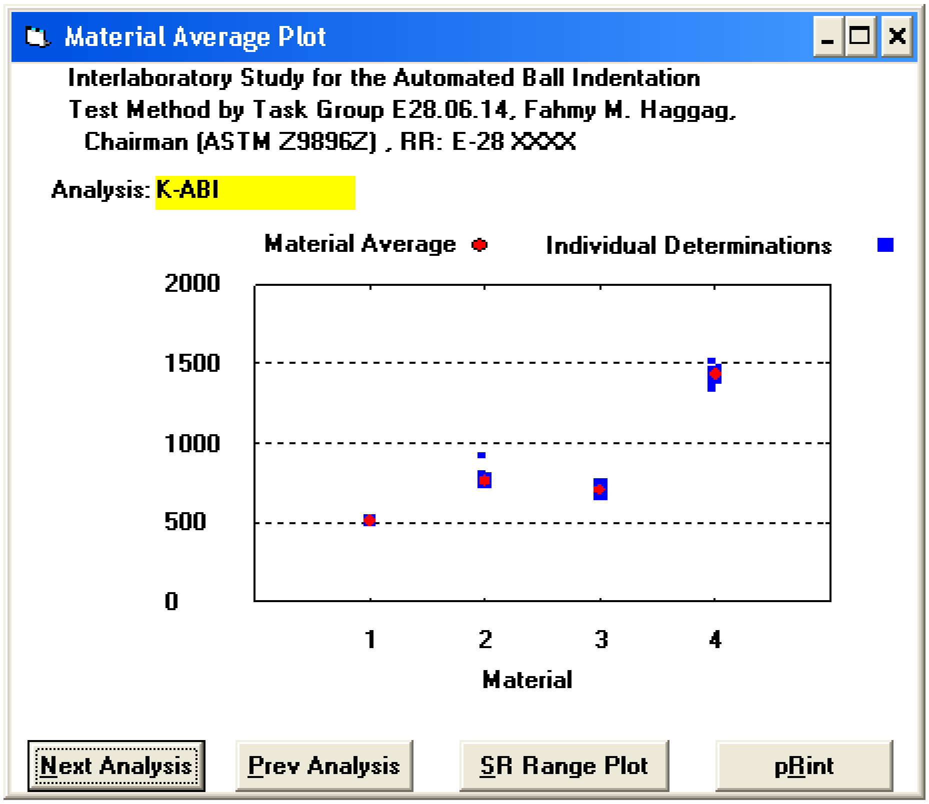
Fig. 4B Plot of the individual and average values of the UTS-ABI, MPa



Interlaboratory Study for the Automated Ball Indentation
Test Method by Task Group E28.06.14, Fahmy M. Haggag,
Chairman (ASTM Z9896Z) , RR: E-28 XXXX

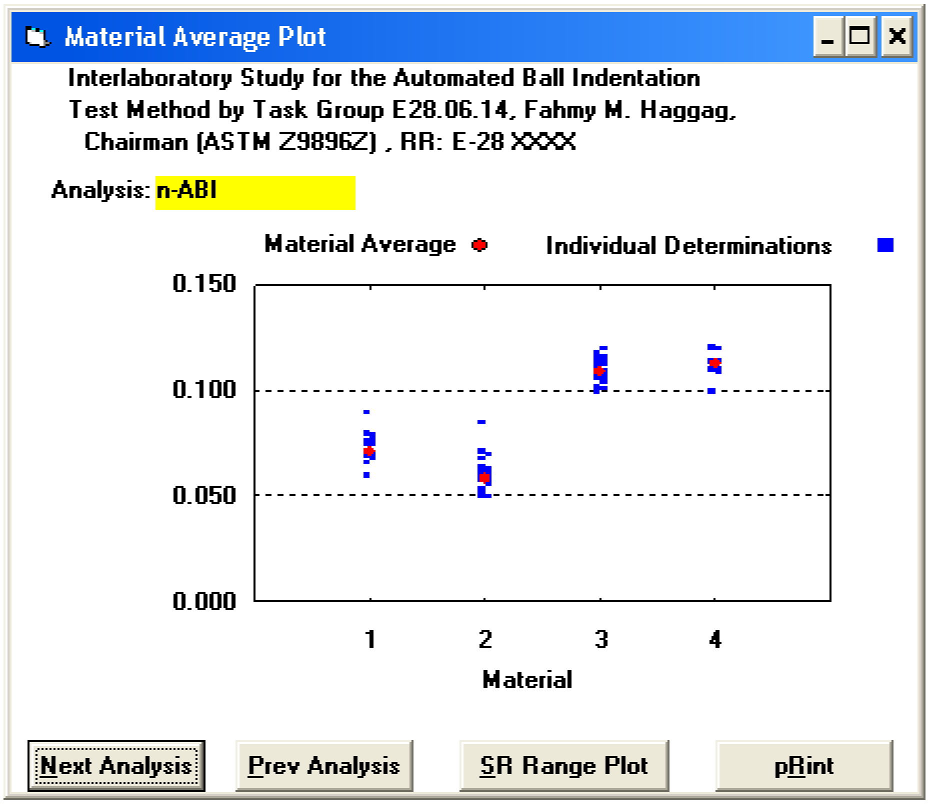
Analysis: UTS-ABI

Fig. 4C Plot of the individual and average values of the K-ABI, MPa


Interlaboratory Study for the Automated Ball Indentation
Test Method by Task Group E28.06.14, Fahmy M. Haggag,
Chairman (ASTM Z9896Z) , RR: E-28 XXXX

Analysis: K-ABI

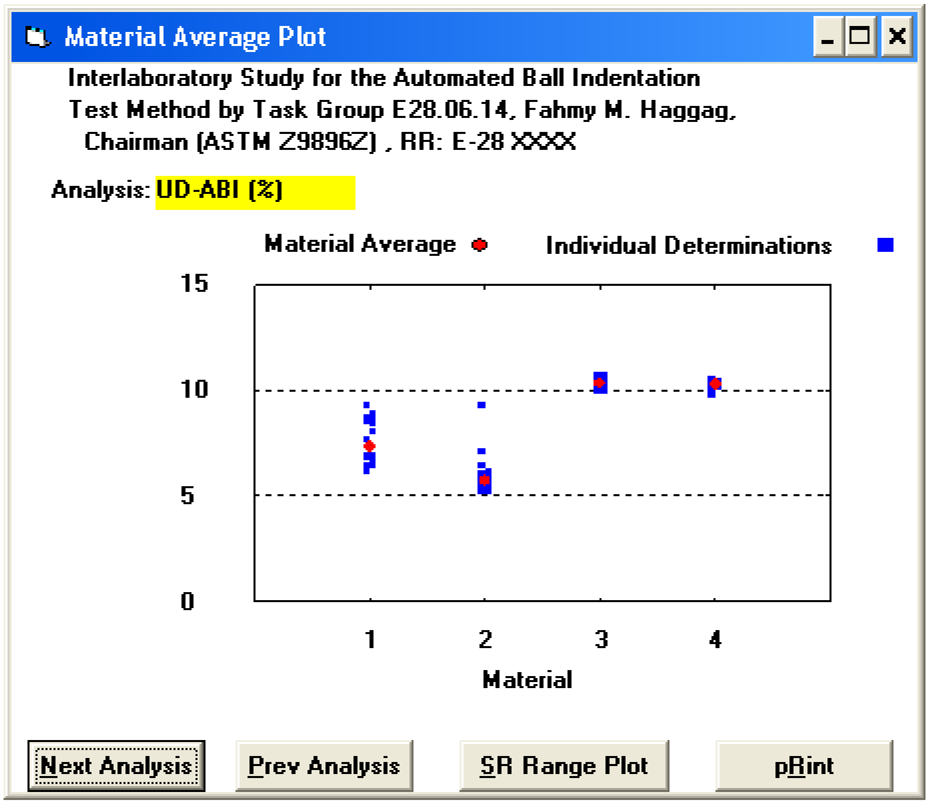
Fig. 4D Plot of the individual and average values of the n-ABI



Interlaboratory Study for the Automated Ball Indentation
Test Method by Task Group E28.06.14, Fahmy M. Haggag,
Chairman (ASTM Z9896Z) , RR: E-28 XXXX

Analysis: n-ABI

Fig. 4E Plot of the individual and average values of the UD-ABI, Percent



Interlaboratory Study for the Automated Ball Indentation Test Method by Task Group E28.06.14, Fahmy M. Haggag, Chairman (ASTM Z9896Z) , RR: E-28 XXXX

Analysis: UD-ABI (%)

APPENDIX A

Summary Tables of ABI Test Results from Six Laboratories and Their Standard Deviations (Calculated Using the Microsoft Excel® Spread Sheet) in Both SI and English Units

Table A1 – ABI Test Results and Their Standard Deviations (Calculated using the Microsoft Excel Spread Sheet Program) From Individual Tests at Six Laboratories, SI Units

Test Name	Yield Strength [MPa]	Estimated Engineering UTS [MPa]	Strength Coefficient, (K) [MPa]	Strain Hardening Exponent (n)	Calculated Uniform Ductility (UD) [%]
	YS-ABI	**UTS-ABI**	**K-ABI**	**n-ABI**	**UD-ABI**
Lab1-A18-1	338	393	502	0.065	6.2
Lab1-A18-2	333	397	512	0.070	6.7
Lab1-A18-3	331	398	517	0.072	7.7
Lab1-A18-4	329	399	521	0.074	8.4
Lab1-A18-5	328	394	511	0.071	7.0
Average	331.8	396.0	512.4	0.070	7.2
Standard Deviation	4.0	2.6	7.2	0.003	0.9
Lab1-A27-1	558	605	741	0.051	5.2
Lab1-A27-2	547	596	736	0.053	5.3
Lab1-A27-3	543	598	742	0.055	5.4
Lab1-A27-4	549	606	750	0.055	5.4
Lab1-A27-5	548	603	747	0.055	5.4
Average	548.9	601.7	743.0	0.054	5.3
Standard Deviation	5.7	4.3	5.8	0.002	0.1
Lab1-S16-1	365	479	668	0.101	10.0
Lab1-S16-2	369	492	690	0.104	10.1
Lab1-S16-3	354	498	714	0.114	10.5
Lab1-S16-4	355	497	712	0.113	10.5
Lab1-S16-5	370	487	680	0.102	10.0
Average	362.5	490.4	693.0	0.107	10.2
Standard Deviation	7.6	8.0	20.1	0.006	0.3
Lab1-S29-1	728	994	1405	0.107	10.1
Lab1-S29-2	723	1009	1440	0.111	10.3
Lab1-S29-3	724	993	1410	0.109	10.1
Lab1-S29-4	729	999	1417	0.108	10.1
Lab1-S29-5	739	971	1354	0.101	9.8
Average	728.5	993.0	1405.1	0.107	10.1
Standard Deviation	6.3	13.9	31.5	0.004	0.2
Lab2-A16-1	340	407	528	0.071	7.0
Lab2-A16-2	335	405	526	0.073	8.1
Lab2-A16-3	338	403	521	0.070	6.8
Lab2-A16-4	337	401	517	0.070	6.7
Lab2-A16-5	332	407	535	0.076	8.7
Average	336.4	404.4	525.3	0.072	7.5
Standard Deviation	3.1	2.6	6.7	0.003	0.9
Lab2-A26-1	562	619	765	0.054	5.4

Lab2-A26-2	550	628	797	0.063	6.0
Lab2-A26-3	543	623	789	0.063	6.0
Lab2-A26-4	547	621	782	0.061	5.8
Lab2-A26-5	550	607	752	0.055	5.4
Average	550.5	619.4	777.1	0.059	5.7
Standard Deviation	7.1	7.6	18.1	0.004	0.3
Lab2-S17-1	359	513	740	0.116	10.8
Lab2-S17-2	360	525	763	0.120	10.8
Lab2-S17-3	377	519	738	0.110	10.3
Lab2-S17-4	365	500	710	0.109	10.3
Lab2-S17-5	359	498	711	0.111	10.4
Average	364.1	510.8	732.3	0.113	10.5
Standard Deviation	7.6	11.7	22.6	0.005	0.3
Lab2-S22-1	729	1013	1444	0.111	10.2
Lab2-S22-2	715	1013	1458	0.115	10.5
Lab2-S22-3	715	1022	1476	0.117	10.5
Lab2-S22-4	720	1020	1469	0.115	10.5
Lab2-S22-5	729	996	1412	0.108	10.1
Average	721.3	1012.7	1451.7	0.113	10.4
Standard Deviation	7.1	10.4	25.4	0.004	0.2
Lab3- A17 Y01	309	394	528	0.085	9.3
Lab3- A17 Y02	332	398	518	0.073	8.1
Lab3- A17 Y03	330	397	518	0.074	8.3
Lab3- A17 Y04	330	393	509	0.071	6.9
Lab3- A17 Y05	330	387	496	0.068	6.4
Average	326.4	393.7	513.9	0.074	7.8
Standard Deviation	9.6	4.4	12.0	0.006	1.2
Lab3- A22 Y01	540	687	923	0.085	9.3
Lab3- A22 Y02	548	631	804	0.065	6.2
Lab3- A22 Y03	532	627	811	0.071	7.1
Lab3- A22 Y04	554	609	757	0.056	5.5
Lab3- A22 Y05	551	613	766	0.058	5.6
Average	545.1	633.2	812.2	0.067	6.7
Standard Deviation	8.9	31.3	66.4	0.012	1.6
Lab3- S14 Y01	349	488	699	0.114	10.5
Lab3- S14 Y02	360	492	699	0.109	10.3
Lab3- S14 Y03	356	478	674	0.106	10.2
Lab3- S14 Y04	365	485	682	0.104	10.1
Lab3- S14 Y05	364	477	664	0.100	10.0
Average	359.0	483.9	683.4	0.107	10.2
Standard Deviation	6.5	6.3	15.3	0.005	0.2
Lab3- S25 Y01	701	972	1394	0.114	10.4
Lab3- S25 Y02	719	979	1390	0.109	10.1
Lab3- S25 Y03	696	1004	1464	0.121	10.5
Lab3- S25 Y04	716	994	1425	0.114	10.5

Lab3- S25 Y05	718	954	1342	0.105	9.9
Average	710.2	980.4	1402.8	0.113	10.3
Standard Deviation	10.7	19.3	45.2	0.006	0.3
Lab4-A15-1	334	399	516	0.070	6.8
Lab4-A15-2	323	394	517	0.076	8.7
Lab4-A15-3	333	392	505	0.069	6.5
Lab4-A15-4	331	392	506	0.069	6.6
Lab4-A15-5	331	387	495	0.066	6.2
Average	330.4	393.0	507.9	0.070	7.0
Standard Deviation	4.5	4.5	9.0	0.004	1.0
Lab4-A29-1	551	603	742	0.053	5.3
Lab4-A29-2	546	603	749	0.056	5.5
Lab4-A29-3	541	605	757	0.058	5.7
Lab4-A29-4	562	607	743	0.050	5.2
Lab4-A29-5	550	596	730	0.051	5.2
Average	549.9	602.7	744.1	0.054	5.4
Standard Deviation	7.7	4.3	9.9	0.003	0.2
Lab4-S19-1	354	488	694	0.110	10.3
Lab4-S19-2	362	475	664	0.101	10.0
Lab4-S19-3	359	484	684	0.107	10.2
Lab4-S19-4	356	486	689	0.108	10.3
Lab4-S19-5	357	499	713	0.113	10.5
Average	357.4	486.2	688.6	0.108	10.3
Standard Deviation	2.8	8.4	17.8	0.004	0.2
Lab4-S26-1	725	996	1414	0.109	10.2
Lab4-S26-2	717	1009	1449	0.114	10.5
Lab4-S26-3	721	998	1423	0.111	10.3
Lab4-S26-4	722	989	1402	0.108	10.1
Lab4-S26-5	719	1006	1441	0.113	10.5
Average	720.9	999.5	1426.0	0.111	10.3
Standard Deviation	3.1	8.3	19.2	0.003	0.2
Lab5-A13-1	334	399	515	0.070	6.8
Lab5-A13-2	334	397	514	0.070	6.7
Lab5-A13-3	328	391	506	0.071	6.8
Lab5-A13-4	329	387	497	0.068	6.4
Lab5-A13-5	323	387	502	0.071	7.0
Average	329.6	392.0	506.6	0.070	6.7
Standard Deviation	4.7	5.6	7.8	0.001	0.2
Lab5-A24-1	538	613	773	0.061	5.9
Lab5-A24-2	540	602	751	0.057	5.6
Lab5-A24-3	549	605	750	0.055	5.5
Lab5-A24-4	545	605	753	0.056	5.5
Lab5-A24-5	532	611	777	0.064	6.1
Average	540.8	607.2	760.9	0.059	5.7
Standard Deviation	6.5	4.6	13.1	0.004	0.3

Lab5-S13-1	356	505	726	0.115	10.7
Lab5-S13-2	363	485	682	0.105	10.1
Lab5-S13-3	356	494	706	0.112	10.4
Lab5-S13-4	361	488	690	0.107	10.2
Lab5-S13-5	356	493	702	0.111	10.4
Average	358.3	492.9	701.2	0.110	10.4
Standard Deviation	3.2	7.6	16.9	0.004	0.2
Lab5-S28-1	714	1039	1508	0.119	10.6
Lab5-S28-2	723	1029	1482	0.116	10.5
Lab5-S28-3	704	1038	1516	0.122	10.5
Lab5-S28-4	735	998	1414	0.108	10.1
Lab5-S28-5	723	1023	1473	0.115	10.5
Average	719.8	1025.1	1478.5	0.116	10.4
Average	11.4	16.8	40.4	0.005	0.2
Standard Deviation	332	397	512	0.070	6.8
Lab6-A10-2	326	399	522	0.075	8.6
Lab6-A1--3	325	398	522	0.076	8.7
Lab6-A10-4	321	400	529	0.079	9.0
Lab6-A10-5	323	394	515	0.075	8.5
Average	325.2	397.3	519.9	0.075	8.3
Standard Deviation	4.0	2.3	6.7	0.003	0.9
Lab6-A20-1	529	623	800	0.068	6.5
Lab6-A20-2	546	612	766	0.058	5.6
Lab6-A20-3	539	614	776	0.062	5.9
Lab6-A20-4	541	612	769	0.060	5.8
Lab6-A20-5	541	607	760	0.058	5.7
Average	538.9	613.6	774.0	0.061	5.9
Standard Deviation	6.3	5.6	15.7	0.004	0.4
Lab6-S10-1	367	511	731	0.112	10.4
Lab6-S10-2	364	516	744	0.116	10.7
Lab6-S10-3	376	520	742	0.111	10.4
Lab6-S10-4	378	513	727	0.108	10.2
Lab6-S10-5	365	525	761	0.118	10.8
Average	369.8	517.1	740.7	0.113	10.5
Standard Deviation	6.6	5.8	13.2	0.004	0.2
Lab6-S20-1	732	1004	1426	0.109	10.1
Lab6-S20-2	727	1014	1449	0.112	10.3
Lab6-S20-3	723	1007	1440	0.112	10.3
Lab6-S20-4	723	1020	1466	0.115	10.5
Lab6-S20-5	730	1014	1445	0.111	10.3
Average	727.2	1011.6	1445.1	0.112	10.3
Standard Deviation	4.1	6.1	14.7	0.002	0.1

	Yield Strength [MPa] **YS-ABI**	Estimated Engineering UTS [MPa] **UTS-ABI**	Strength Coefficient, (K) [MPa] **K-ABI**	Strain Hardening Exponent (n) **n-ABI**	Calculated Uniform Ductility [%] **UD-ABI**
A1X Material					
Avg. Avg.	330.0	396.1	514.3	0.072	7.4
Avg. Standard Deviation	5.0	3.7	8.2	0.003	0.8
A2X Material					
Avg. Avg.	545.7	613.0	768.6	0.059	5.8
Avg. Standard Deviation	7.0	9.6	21.5	0.005	0.5
S1X Material					
Avg. Avg.	361.9	496.9	706.6	0.110	10.3
Avg. Standard Deviation	5.7	7.9	17.6	0.005	0.2
S2X Material					
Avg. Avg.	721.3	1003.7	1434.9	0.112	10.3
Avg. Standard Deviation	7.1	12.5	29.4	0.004	0.2

Table A2 – ABI Test Results and Their Standard Deviations (Calculated using the Microsoft Excel Spread Sheet Program) From Individual Tests at Six Laboratories, English Units

Test Name	Yield Strength [ksi] **YS-ABI**	Estimated Engineering UTS [ksi] **UTS-ABI**	Strength Coefficient, (K) [ksi] **K-ABI**	Strain Hardening Exponent (n) **n-ABI**	Calculated Uniform Ductility [%] **UD-ABI**
Lab1-A18-1	49.0	57.0	72.7	0.065	6.2
Lab1-A18-2	48.2	57.5	74.3	0.070	6.7
Lab1-A18-3	48.0	57.7	74.9	0.072	7.7
Lab1-A18-4	47.7	57.9	75.6	0.074	8.4
Lab1-A18-5	47.6	57.1	74.1	0.071	7.0
Average	48.1	57.4	74.3	0.070	7.2
Standard Deviation	0.6	0.4	1.1	0.003	0.9
Lab1-A27-1	81.0	87.7	107.4	0.051	5.2
Lab1-A27-2	79.4	86.5	106.7	0.053	5.3
Lab1-A27-3	78.7	86.7	107.6	0.055	5.4
Lab1-A27-4	79.5	87.9	108.8	0.055	5.4
Lab1-A27-5	79.5	87.5	108.3	0.055	5.4
Average	79.6	87.3	107.8	0.054	5.3
Standard Deviation	0.8	0.6	0.8	0.002	0.1
Lab1-S16-1	52.9	69.4	96.9	0.101	10.0
Lab1-S16-2	53.5	71.3	100.1	0.104	10.1
Lab1-S16-3	51.3	72.2	103.6	0.114	10.5
Lab1-S16-4	51.5	72.1	103.3	0.113	10.5
Lab1-S16-5	53.6	70.6	98.7	0.102	10.0
Average	52.6	71.1	100.5	0.107	10.2
Standard Deviation	1.1	1.2	2.9	0.006	0.3
Lab1-S29-1	105.5	144.1	203.8	0.107	10.1
Lab1-S29-2	104.9	146.3	208.8	0.111	10.3
Lab1-S29-3	105.0	144.0	204.5	0.109	10.1
Lab1-S29-4	105.7	144.9	205.5	0.108	10.1
Lab1-S29-5	107.2	140.8	196.4	0.101	9.8
Average	105.7	144.0	203.8	0.107	10.1
Standard Deviation	0.9	2.0	4.6	0.004	0.2
Lab2-A16-1	49.3	59.0	76.5	0.071	7.0
Lab2-A16-2	48.6	58.7	76.3	0.073	8.1
Lab2-A16-3	49.1	58.5	75.6	0.070	6.8
Lab2-A16-4	48.9	58.1	75.0	0.070	6.7
Lab2-A16-5	48.1	59.0	77.5	0.076	8.7
Average	48.8	58.7	76.2	0.072	7.5
Standard Deviation	0.5	0.4	0.9	0.003	0.9
Lab2-A26-1	81.5	89.7	111.0	0.054	5.4

Lab2-A26-2	79.7	91.1	115.6	0.063	6.0
Lab2-A26-3	78.8	90.3	114.5	0.063	6.0
Lab2-A26-4	79.3	90.0	113.4	0.061	5.8
Lab2-A26-5	79.8	88.1	109.1	0.055	5.4
Average	79.8	89.8	112.7	0.059	5.7
Standard Deviation	1.0	1.1	2.6	0.004	0.3
Lab2-S17-1	52.1	74.4	107.3	0.116	10.8
Lab2-S17-2	52.2	76.1	110.7	0.120	10.8
Lab2-S17-3	54.7	75.2	107.0	0.110	10.3
Lab2-S17-4	53.0	72.5	102.9	0.109	10.3
Lab2-S17-5	52.1	72.2	103.1	0.111	10.4
Average	52.8	74.1	106.2	0.113	10.5
Standard Deviation	1.1	1.7	3.3	0.005	0.3
Lab2-S22-1	105.7	146.9	209.4	0.111	10.2
Lab2-S22-2	103.7	146.9	211.5	0.115	10.5
Lab2-S22-3	103.7	148.2	214.0	0.117	10.5
Lab2-S22-4	104.4	148.0	213.1	0.115	10.5
Lab2-S22-5	105.7	144.4	204.8	0.108	10.1
Average	104.6	146.9	210.6	0.113	10.4
Standard Deviation	1.0	1.5	3.7	0.004	0.2
Lab3- A17 Y01	44.9	57.1	76.6	0.085	9.3
Lab3- A17 Y02	48.2	57.7	75.1	0.073	8.1
Lab3- A17 Y03	47.9	57.6	75.1	0.074	8.3
Lab3- A17 Y04	47.9	57.0	73.9	0.071	6.9
Lab3- A17 Y05	47.9	56.1	72.0	0.068	6.4
Average	47.4	57.1	74.5	0.074	7.8
Standard Deviation	1.4	0.6	1.7	0.006	1.2
Lab3- A22 Y01	78.3	99.6	133.9	0.085	9.3
Lab3- A22 Y02	79.4	91.5	116.6	0.065	6.2
Lab3- A22 Y03	77.2	90.9	117.6	0.071	7.1
Lab3- A22 Y04	80.4	88.3	109.8	0.056	5.5
Lab3- A22 Y05	80.0	88.9	111.0	0.058	5.6
Average	79.1	91.8	117.8	0.067	6.7
Standard Deviation	1.3	4.5	9.6	0.012	1.6
Lab3- S14 Y01	50.6	70.7	101.4	0.114	10.5
Lab3- S14 Y02	52.3	71.3	101.3	0.109	10.3
Lab3- S14 Y03	51.7	69.3	97.7	0.106	10.2
Lab3- S14 Y04	52.9	70.4	98.9	0.104	10.1
Lab3- S14 Y05	52.9	69.2	96.3	0.100	10.0
Average	52.1	70.2	99.1	0.107	10.2
Standard Deviation	1.0	0.9	2.2	0.005	0.2
Lab3- S25 Y01	101.7	140.9	202.1	0.114	10.4
Lab3- S25 Y02	104.3	142.0	201.5	0.109	10.1
Lab3- S25 Y03	101.0	145.6	212.3	0.121	10.5
Lab3- S25 Y04	103.9	144.1	206.7	0.114	10.5

Lab3- S25 Y05	104.2	138.4	194.6	0.105	9.9
Average	103.0	142.2	203.4	0.113	10.3
Standard Deviation	1.6	2.8	6.6	0.006	0.3
Lab4-A15-1	48.5	57.9	74.8	0.070	6.8
Lab4-A15-2	46.8	57.2	75.0	0.076	8.7
Lab4-A15-3	48.3	56.9	73.3	0.069	6.5
Lab4-A15-4	48.0	56.9	73.4	0.069	6.6
Lab4-A15-5	48.0	56.1	71.8	0.066	6.2
Average	47.9	57.0	73.7	0.070	7.0
Standard Deviation	0.7	0.6	1.3	0.004	1.0
Lab4-A29-1	80.0	87.4	107.6	0.053	5.3
Lab4-A29-2	79.2	87.5	108.7	0.056	5.5
Lab4-A29-3	78.4	87.7	109.8	0.058	5.7
Lab4-A29-4	81.4	88.1	107.7	0.050	5.2
Lab4-A29-5	79.7	86.4	105.9	0.051	5.2
Average	79.7	87.4	107.9	0.054	5.4
Standard Deviation	1.1	0.6	1.4	0.003	0.2
Lab4-S19-1	51.4	70.7	100.6	0.110	10.3
Lab4-S19-2	52.4	68.9	96.3	0.101	10.0
Lab4-S19-3	52.0	70.2	99.2	0.107	10.2
Lab4-S19-4	51.6	70.5	99.9	0.108	10.3
Lab4-S19-5	51.8	72.3	103.4	0.113	10.5
Average	51.8	70.5	99.9	0.108	10.3
Standard Deviation	0.4	1.2	2.6	0.004	0.2
Lab4-S26-1	105.2	144.4	205.1	0.109	10.2
Lab4-S26-2	104.1	146.4	210.2	0.114	10.5
Lab4-S26-3	104.5	144.7	206.4	0.111	10.3
Lab4-S26-4	104.8	143.4	203.4	0.108	10.1
Lab4-S26-5	104.3	145.9	209.0	0.113	10.5
Average	104.6	145.0	206.8	0.111	10.3
Standard Deviation	0.4	1.2	2.8	0.003	0.2
Lab5-A13-1	48.5	57.8	74.7	0.070	6.8
Lab5-A13-2	48.4	57.6	74.5	0.070	6.7
Lab5-A13-3	47.6	56.7	73.4	0.071	6.8
Lab5-A13-4	47.7	56.1	72.1	0.068	6.4
Lab5-A13-5	46.8	56.1	72.7	0.071	7.0
Average	47.8	56.9	73.5	0.070	6.7
Standard Deviation	0.7	0.8	1.1	0.001	0.2
Lab5-A24-1	78.0	88.9	112.1	0.061	5.9
Lab5-A24-2	78.3	87.3	108.9	0.057	5.6
Lab5-A24-3	79.6	87.8	108.8	0.055	5.5
Lab5-A24-4	79.1	87.7	109.2	0.056	5.5
Lab5-A24-5	77.2	88.6	112.7	0.064	6.1
Average	78.4	88.1	110.3	0.059	5.7
Standard Deviation	0.9	0.7	1.9	0.004	0.3

Lab5-S13-1	51.7	73.2	105.3	0.115	10.7
Lab5-S13-2	52.6	70.3	98.9	0.105	10.1
Lab5-S13-3	51.6	71.6	102.3	0.112	10.4
Lab5-S13-4	52.3	70.8	100.0	0.107	10.2
Lab5-S13-5	51.7	71.5	101.9	0.111	10.4
Average	52.0	71.5	101.7	0.110	10.4
Standard Deviation	0.4	1.1	2.5	0.004	0.2
Lab5-S28-1	103.6	150.7	218.7	0.119	10.6
Lab5-S28-2	104.9	149.2	215.0	0.116	10.5
Lab5-S28-3	102.2	150.5	219.8	0.122	10.5
Lab5-S28-4	106.6	144.7	205.0	0.108	10.1
Lab5-S28-5	104.8	148.3	213.6	0.115	10.5
Average	104.4	148.7	214.4	0.116	10.4
Standard Deviation	1.6	2.4	5.9	0.005	0.2
Lab6-A10-1	48.1	57.5	74.3	0.070	6.8
Lab6-A10-2	47.3	57.8	75.6	0.075	8.6
Lab6-A1--3	47.1	57.7	75.7	0.076	8.7
Lab6-A10-4	46.5	58.0	76.7	0.079	9.0
Lab6-A10-5	46.9	57.1	74.6	0.075	8.5
Average	47.2	57.6	75.4	0.075	8.3
Standard Deviation	0.6	0.3	1.0	0.003	0.9
Lab6-A20-1	76.7	90.3	116.1	0.068	6.5
Lab6-A20-2	79.2	88.8	111.0	0.058	5.6
Lab6-A20-3	78.1	89.1	112.5	0.062	5.9
Lab6-A20-4	78.4	88.7	111.5	0.060	5.8
Lab6-A20-5	78.4	88.1	110.2	0.058	5.7
Average	78.2	89.0	112.3	0.061	5.9
Standard Deviation	0.9	0.8	2.3	0.004	0.4
Lab6-S10-1	53.2	74.1	106.0	0.112	10.4
Lab6-S10-2	52.8	74.9	107.9	0.116	10.7
Lab6-S10-3	54.5	75.4	107.6	0.111	10.4
Lab6-S10-4	54.8	74.4	105.4	0.108	10.2
Lab6-S10-5	52.9	76.2	110.3	0.118	10.8
Average	53.6	75.0	107.4	0.113	10.5
Standard Deviation	0.9	0.8	1.9	0.004	0.2
Lab6-S20-1	106.2	145.6	206.8	0.109	10.1
Lab6-S20-2	105.5	147.0	210.1	0.112	10.3
Lab6-S20-3	104.9	146.1	208.8	0.112	10.3
Lab6-S20-4	104.9	147.9	212.7	0.115	10.5
Lab6-S20-5	105.9	147.0	209.6	0.111	10.3
Average	105.5	146.7	209.6	0.112	10.3
Standard Deviation	0.6	0.9	2.1	0.002	0.1

	Yield Strength [ksi] **YS-ABI**	Estimated Engineering UTS [ksi] **UTS-ABI**	Strength Coefficient, (K) [ksi] **K-ABI**	Strain Hardening Exponent (n) **n-ABI**	Calculated Uniform Ductility [%] **UD-ABI**
A1X Material					
Avg. Avg.	47.9	57.4	74.6	0.072	7.4
Avg. Standard Deviation	0.7	0.5	1.2	0.003	0.8
A2X Material					
Avg. Avg.	79.1	88.9	111.5	0.059	5.8
Avg. Standard Deviation	1.0	1.4	3.1	0.005	0.5
S1X Material					
Avg. Avg.	52.5	72.1	102.5	0.110	10.3
Avg. Standard Deviation	0.8	1.2	2.6	0.005	0.2
S2X Material					
Avg. Avg.	104.6	145.6	208.1	0.112	10.3
Avg. Standard Deviation	1.0	1.8	4.3	0.004	0.2

Designation: X XXXX-XX — Z9896Z

Standard Test Methods for
Automated Ball Indentation Testing of Metallic Samples and Structures to Determine Stress-Strain Curves and Ductility at Various Test Temperatures[1]

1. Scope

1.1. These methods cover the determination of the true-stress versus true-plastic-strain curves of metallic materials and structural components using an automated ball indentation (ABI) test technique. They can be used for any metallic material with thickness greater than 0.25 mm (0.010 in). They require a surface that is smooth and that has a minimum distance of 0.50 mm (0.02 in) between free edges. The ABI test methods can be performed using a laboratory bench-top instrument or a portable field device.

1.2. The ABI test can be conducted at sample temperatures ranging from -196 to 427°C (-320 to 800°F). Testing at higher temperatures can be performed provided that the test surface is not severely altered by oxidation or corrosion during the test.

1.3. The purpose of the ABI test methods is to determine tensile properties (including true-stress versus true-plastic-strain curve, yield strength, uniform ductility, strain-hardening exponent, ultimate strength, and Lüders strain) as a nondestructive and localized alternative to the destructive tensile test methods conducted according to ASTM standards E 8, E 21, and E 646.

1.4. *This standard does not purport to address all of the safety concerns, if any, associated with its use. It is the responsibility of the user of this standard to establish appropriate safety and health practices and determine the applicability of regulatory limitations prior to use.*

2. Referenced Documents

2.1. *ASTM Standards:*

E 4	Practices for Force Verification of Testing Machines
E 6	Terminology Relating to Methods of Mechanical Testing
E 8	Test Methods for Tension Testing of Metallic Materials
E 21	Test Methods for Elevated Temperature Tension Tests of Metallic Materials
E 74	Practice for Calibration of Force Measuring Instruments for Verifying the Force Indication of Testing Machines
E 646	Test Methods for Tensile Strain-Hardening Exponents (*n*-Values) of Metallic Sheet Materials

3. Terminology

3.1. *Definitions*—The definitions of terms relating to tensile testing appearing in Terminology E 6 shall be considered as applying to the terms used in these test methods of automated ball

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[1] These test methods are under the jurisdiction of ASTM Committee E-28 on Mechanical Testing and are the direct responsibility of Subcommittee E28.06 on Indentation Testing.

indentation (ABI) testing. Additional and new terms related to this standard are defined as follows:

3.1.1 *Force-depth partial unloading slope* [FL^{-1}]—the ratio of spherical indentation force to indentation depth increment during the upper 50% unloading.

3.1.2. *Meyer's index, m*—a material constant related to the strain hardening of the metal.

3.1.3. *Yield parameter (A)* [FL^{-2}]—a test material parameter related to the yield strength and strain hardening of the metal that expresses the resistance of metal to penetration by a spherical indenter.

3.1.4. *Material's yield slope (β_m)*—a material type constant related to the yield strength of each class of metal (e.g., aluminum, ferritic steel, stainless steel, titanium, uranium alloys, etc.).

NOTE--It is an empirical value similar to the 0.2% offset value of the yield strength as defined in the uniaxial tensile test.

3.1.5. *ABI-derived yield strength (σ_y)* [FL^{-2}]—an ABI parameter that is related to the 0.2% offset yield strength from tensile tests of most metallic materials.

3.1.6. *Constraint factor (α_m)*—a material constant related to the resistance of metal to plastic spherical deformation within a specific range of strain rate or indenter speed.

3.1.7. *Effective ball indentation strain rate ($\acute{\varepsilon}$)*—the average strain rate from all indentation cycles performed at a single test location during a complete ABI test.

NOTE--The ball indenter strain rate ($\acute{\varepsilon}$) for each cycle is the ratio of indenter velocity (v) to the indentation chordal diameter (d_t) multiplied by 0.4 ($\acute{\varepsilon} = 0.4\, v/d_t$).

3.1.8. *Strain-hardening exponent (n)*—the exponent in the empirical relationship between true-stress (σ_t) and true-plastic-strain (ε_p), $\sigma_t = K\varepsilon_p^{\,n}$.

NOTE--It is computed as the slope of the E 646 assumed linear relationship between logarithm true-stress and logarithm true-plastic-strain.

3.1.9. *Strength coefficient (K)* [FL^{-2}]—an experimental constant, computed from the fit of the data to the assumed power law (described in E 646) that is numerically equal to the extrapolated value of true stress at a true-plastic-strain value of 1.00.

3.1.10 *Discontinuous yielding or Lüders strain (ε_L)*—in a uniaxial test, a hesitation or fluctuation of force, such as is sometimes observed at or near the onset of plastic deformation, due to localized yielding (The stress-strain curve need not appear to be discontinuous.)

NOTE-- In an ABI test the Lüders strain behavior is manifested in the material pile-up around the indentation. In an ABI test Lüders strain is calculated from its relationship with the material yield strength, strain-hardening exponent, and strength coefficient.

4. Summary of Test Methods

4.1 A spherical (ball) indenter is forced into the surface of a metallic sample or a structural component. The spherical shape of the indenter causes an increasing strain with increased indentation depth up to a maximum of 0.2 or 20% true-plastic-strain. A true strain of 20% corresponds to a penetration depth equal to the indenter radius. The penetration depth of the spherical indenter into the test surface is measured with a spring-loaded linear variable differential transformer (LVDT). The current strain produced is a function of the penetration depth. The force required to indent the material to increased depth values is measured with a load cell. The current stress at any time is a function of the current indentation force. Periodic partial unloadings during the test are used to determine the elastic strain. The elastic strain is subtracted from the total strain to give the plastic strain. The incremental values of the ABI-measured true-stress and true-plastic-strain are calculated from the indentation force-depth data (based on elasticity and plasticity theories) and plotted to form a true-stress versus true-plastic-strain curve of the material. The ABI-derived yield strength is determined from the force-depth data. Other properties, including the strain-hardening exponent (n), strength coefficient (K), Lüders strain (ε_L), uniform ductility, and ultimate tensile strength (UTS), may also be determined from the ABI test. Also, the ABI test can be performed without intermediate partial unloadings (i.e., in a single cycle of continuous loading up to the desired maximum indentation depth/strain followed by complete unloading). This approach is preferred for high temperature or high strain rate testing to avoid indentation creep and nonlinear unloading slopes, respectively. The single cycle ABI test produces a curve of true-stress versus true-strain (i.e., total true strain since the elastic strain component cannot be subtracted due to the elimination of partial unloadings).

4.2 The entire test is fully automated (computer-controlled) where the spherical indenter is driven into the test surface at a desired speed which controls the strain rate of the ABI test, and the indentation force versus penetration depth are continuously collected (using a 16-bit resolution data acquisition system or better) during the entire test.

4.3 For laboratory specimens, the test samples can be cooled or heated to the desired ABI test temperature [-196°C to 427°C (-320°F to 800°F)] using an environmental chamber to bring both test sample and indenter to the desired test temperature while the load cell and the LVDT are kept outside the chamber. A temperature-resistant LVDT or a clip gage can be used inside the environmental chamber. Testing at higher temperatures can be performed provided that the test surface is not severely oxidized (e.g., by utilizing an inert gas or a vacuum chamber).

5. Significance and Use

5.1 The stress-strain curve measured with the ABI test has been demonstrated to correlate with the stress-strain curve measured in a tensile test. The localized ABI test is nondestructive and can be used in-situ to measure the stress-strain properties of a material sample or of a component part in service. Therefore, it can be used to measure stress-strain properties where insufficient material is available to use in a destructive tensile test. The ABI test leaves a shallow spherical depression on the test surface with no sharp edges (hence, no stress concentration or crack initiation sites). Furthermore, it leaves a favorable compressive residual stress at the test site (similar to shot peening but on a slightly larger scale). The ABI test is also useful in testing small volumes of welds and irregularly shaped heat-affected-zones (HAZs).

5.2 The ABI test is particularly useful where a life extension evaluation is planned for a component and adequate materials property data are not available. Also, it can be used to measure properties for materials that may have service damage that has caused a change in tensile properties during service life (e.g. neutron embrittlement of nuclear pressure vessels). Another important application is the determination of yield strength of ferritic steel components, such as oil and gas pipelines, when no documentation exists for the original and/or repair material and when a deterministic fitness-for-service evaluation is required for safe operation at current or higher (up-rated) pressures.

5.3 The ABI test is a macroscopic/bulk technique that measures the properties on a small volume of material. This capability is valuable in mapping out property gradients in welds and HAZs. The minimum diameter of the indenter must be large enough such that the spherical indentation, produced at the smallest practical depth/strain, covers at least five grains of the metallic sample. This requirement is the same for the minimum thickness of a tensile specimen in order to measure macroscopic/bulk properties. The ABI technique can be used to measure the stress-strain properties of a material that may have a sharp gradient of mechanical properties. This, for example, exists in a weldment where the base metal and the weld metal have different strength and ductility and the HAZ may have a very sharp gradient of properties. Here the ABI test can measure the flow properties (true-stress versus true-plastic-strain curve) of a small volume of material and can measure the strength profile along a line traversing from one base metal through the HAZ, the weld metal and continuing through the other base metal.

5.4 Although the ABI test is nondestructive, the strain-hardening exponent (n) determined from the test is a function of the uniform plastic strain of many metallic materials with a power-law true-stress versus true-plastic-strain curve (e.g. nuclear pressure vessels and carbon steel materials).

5.5 Although there is no necking (similar to that occurring at maximum force in a tensile test), the uniform ductility and ultimate tensile strength are determined from the plot of true-stress versus engineering strain.

5.6 The value of Lüders strain (an important property for evaluating steel sheet metals in automotive industry) is calculated from the ABI-measured yield strength, strain-hardening exponent, and strength coefficient.

6. Apparatus

6.1 *Testing Machines*—Machines used for ABI testing on metal samples or structures shall conform to the requirements of U.S. Patent No. 4,852,397 and Practices E 4. It is important to note that the hardware of both bench-top and field ABI testing machines as well as the ABI testing procedures are patented technologies.[2] The patented testing equipment (bench-top: Stress-Strain Microprobe system, Models SSM-B1000 and SSM-B4000, and the field apparatus: Stress-Strain Microprobe system, Model SSM-M1000) has a trademark and is manufactured by Advanced Technology Corporation.[3]

6.2 The forces used in determining the true-stress versus true-plastic-strain curve from an ABI test with a certain diameter indenter shall be within the verified loading range of the testing machine as defined in Practices E4 (Standard Practices for Force Verification of Testing Machines). The maximum ABI force depends on the indenter diameter, maximum indentation depth, and the flow properties of the metal test sample or structure. The load cell capacity should be appropriate for the indenter diameter and the test material flow properties. The error for forces within the loading range of the testing machine shall not exceed ±1.0%. The non-linearity and non-repeatability of the load cell shall not exceed ± 0.1% and ± 0.03% of the full scale (maximum capacity) of the load cell, respectively. The temporary attachment method (e.g., manual or electric magnets, v-blocks with mechanical clamps, etc.) should ensure: (a) perpendicularity of the indenter axis (within 2.0°) to the test surface, and (b) enough pull force to counter the maximum indentation push force plus the weight of the load frame of the portable testing machine. The minimum components of the testing machine include a rigid load frame suitable for bench-top or field applications (for metal component testing), a driving mechanism (such as an electric servo-motor and a mechanical actuator), an appropriate capacity load cell, a gripping device for holding the indenter, a bracket for holding the displacement transducer (e.g., a spring-loaded Linear Variable Differential Transformer “LVDT”), a high resolution 16-bit data acquisition card or better, and a computer (either a desk-top or a laptop) with appropriate software and interface to the data acquisition card and the servo-motor to provide complete control of the ABI test as well as post-test data analysis. The complete automation of the testing machine should provide closed loop operation with continuous measurement and software limits on both the force and depth signals. The software limits prevent possible damage to the force or depth sensors and avoid violating the depth requirement for a valid ABI test.

6.3 *Indentation depth measurement and calibration*—a high-resolution depth sensor with a full range not greater than 1.0 mm (such as a spring-loaded LVDT) is used for ABI testing. The linearity of

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[2] United States Patent Number 4,852,397 (filed March 15, 1989 and issued August 1, 1989), Fahmy M. Haggag inventor, Advanced Technology Corporation (Oak Ridge, Tennessee, USA) Licensee.

[3] The sole source of supply of the trademarked Stress-Strain Microprobe (SSM) systems known to the committee at this time is Advanced Technology Corporation, 1066 Commerce Park Drive, Oak Ridge, TN 37830-8026, USA, website: www.atc-ssm.com. If you are aware of alternative suppliers, please provide this information to ASTM International Headquarters. Any alternative supplier should not infringe on any existing patent. Your comments will receive careful consideration at a meeting of the responsible technical committee, which you may attend.

the LVDT shall be greater than 0.20% of the full range output, and the repeatability shall be better than 0.00010 mm (0.000004 in). The depth transducer is mounted on a bracket attached to the indenter holder. The LVDT is calibrated using a micrometer with 0.001 mm resolution.

6.4 *Indenters*—The spherical indenter shall be polished and free of surface defects. The tolerance shall be ± 0.003 mm or better in any diameter of the indenter. Spherical indenters made from either tungsten carbide or silicon nitride where the spherical tip and the indenter stem are manufactured from the same material are used for ABI testing of metal samples and structural components. Spherical indenters with various diameters (e.g., 0.254-mm, 0.508-mm, 0.762-mm, and 1.575-mm with a deviation from these values of not more than 0.003 mm in any diameter) can be used for ABI testing depending on the test volume available and the grain size of the test metal. The tungsten carbide indenter shall have an elastic modulus at room temperature greater than 620 GPa and Vickers hardness not less than 1500. Silicon nitride indenters, with Vickers hardness of 1600 or higher and an elastic modulus at room temperature greater than 320 GPa, are recommended for use at test temperatures above 400ºC and up to 1000ºC. The indenter holder, such as a stainless steel chuck, should provide easy interchangeability of indenters, solid support of the indenter stem, and ensure the perpendicularity of the indenter tip to the test surface. The indenter diameter is selected based on the test volume (thickness, final indentation depth, and available test area) and the grain size of the metal. Whenever possible the largest size indenter is selected to increase the test volume and to increase precision. Small indenters such as the 0.254-mm diameter require very smooth surface finish using at least 600-grit polishing. The maximum indentation depth must be less than 10% of the specimen thickness, and the indentation chordal diameter must be enclosed within the desired test material including small welds or HAZ. Appropriate capacity load cells should be used for each size indenter for increased resolution (e.g., 4.45 kN, 1.11 kN, 445 N, and 222 N load cells are appropriate for indenter diameters of 1.575-mm, 0.762-mm, 0.508-mm, and 0.254-mm, respectively).

6.5 *Load-frame attachments for field-testing of pipelines and pressure vessels*—Various attachment methods can be used to temporarily attach the load frame of the portable/field testing machine to structural metal components. These attachments (e.g., manual or electric magnets for magnetic components such as carbon steel pipelines and pressure vessels, v-blocks with mechanical clamps for non-magnetic materials such as stainless steel pipes, etc.) should ensure: (a) perpendicularity of the indenter to the test surface (the angle between the indenter force line and the test surface shall be 90 ± 2º), and (b) enough pull force to counter the maximum indentation push force plus the weight of the load frame of the portable testing machine.

7. Specimen/Structural Preparation

7.1 *Surface finish and optional sample mounting*—The ABI test location should have a smooth machined/ground surface or it must be polished up to 400 grit or better. Small indenters such as the 0.254-mm diameter require very smooth surface finish using at least 600-grit polishing. An irregular or very small sample should be mounted in Bakelite or a similar hard material with the top and bottom surfaces parallel. A rigid swivel sample holder should be used if the mounted sample does not have parallel surfaces. The ABI test area of a metal component must be polished locally using hand held equipment. Other component areas must be prepared properly for the attachments used (e.g., any rust must be removed from carbon steel pipelines in order for the magnetic attachments to secure the load frame of the portable machine to the pipeline test location). When indentations are made on a curved surface, the minimum radius of curvature of the surface shall be not less than 25 times the diameter of the ball indenter.

7.2 *Locating indentation positions*—The planar spacing of indentations must be at least two diameters from their centers and within at least one diameter from free edges.

8. Test Procedure

8.1 *Objective and Overview*--The overall objective of the test methods is to develop ABI force-depth curves that can be used to calculate the yield strength, true-stress versus true-plastic-strain curve, strain-hardening exponent, strength coefficient, uniform ductility, and ultimate strength. Two procedures can be used: *(1)* a multi-cycle ABI test with intermediate partial unloadings or *(2)* a single-cycle ABI test with no intermediate partial unloadings.

8.2 *Initial test preload*—An initial test preload is required for calculating the zero indentation point, on the ABI force-depth curve, at which the ball indenter contacts the test surface for the first time. A small indentation preload (less than 10% of the indentation force at a depth value of 30% of the indenter radius), appropriate to the indenter diameter, is applied to the sample or structure before the continuation of the ABI test. Minimum suggested preloads for the four indenter diameters of 0.254-mm, 0.508-mm, 0.762-mm, and 1.575-mm are 2 N, 5 N, 10 N, and 30 N, respectively). After the preload application, the depth transducer value, indicated on the computer screen, must be small enough to ensure that there is enough remaining range of depth measurement to complete the test up to the user-specified final indentation depth. Immediately after the application of the preload, the ABI test is continued according to either the Multi-Cycle or the Single-Cycle procedures described in 8.3 and 8.4, respectively.

8.3 *Multi-Cycle ABI test*—The procedure involves progressive loading of the ball indenter into the test surface up to a final depth/strain (e.g., 30% of the indenter radius relates to approximately 15% strain). A minimum of five cycles shall be performed at a single ABI test location with equal increments of indentation depth. All intermediate cycles include partial unloading of the indenter (by a determined percentage of 30 –50% of the maximum cycle-force depending on the data acquisition rate). The specimen is fully unloaded at the end of the test. All indentation loading and unloading are performed with a constant indenter speed during the entire ABI test. The force-depth data is collected (using a 16-bit data acquisition system or better) and displayed in real-time on the computer screen during the complete ABI test. The ABI test is fully computer controlled with closed-loop software limits on both force and depth data. If during the test any limit is reached, the loading process is immediately halted and the test area is unloaded. The unloading slopes are linear because of the elastic recovery of the test volume. These slopes are not parallel and increase with increasing indentation depth as the deformation volume increases while the sample elastic modulus does not change with indentation depth. Fig.1 shows a schematic of cyclic loading and unloading of a ball indenter into the surface of test material: (a) Schematic of applied force versus indentation depth, (b) Indentation geometry during force application and after force removal (complete unloading).

8.4 *Single-Cycle ABI Test*—The ABI test can be performed without intermediate partial unloadings (i.e., in a single cycle of continuous loading up to the desired maximum indentation depth/strain followed by complete unloading). This approach is preferred for high temperature or high strain rate testing to avoid indentation creep and nonlinear unloading slopes, respectively. The single cycle ABI test produces a curve of true-stress versus true-strain (i.e., total true strain since the elastic strain component cannot be subtracted due to the elimination of partial unloadings).

9. Calculation of Results

9.1 *Calculation of indentation depth associated with initial test preload*—Linear regression is performed on the force-depth data of the best linear part of the first loading cycle in a Multiple-Cycle ABI test or from the early part (first 5%) of the force-depth curve in a Single-Cycle ABI test. The intersection of the extrapolation of the linear regression fit with the X-axis determines the depth value associated with the preload value. Hence, this indentation depth value is added as a correction or adjustment to all depth data of the raw force-depth curve previously collected with temporarily assuming a zero depth associated with the preload value as shown in Fig. 2. This adjustment results in a lateral shift of the raw force-depth curve to the right by the amount determined from the data regression shown in Fig. 3. The corrected/adjusted ABI force-depth data is shown in Fig. 4.

NOTE 1--The force-depth curve of an ABI test is linear because of the effect of the strain hardening behavior of metallic materials on the shape of the force-depth curve. A nonlinear/ball indenter produces increasing strain values with increasing depth while a linear indenter produces a single value of strain regardless of depth and a nonlinear (concave) force-depth curve. Hence, a stress-strain curve can be produced only using a nonlinear indenter. ABI test results on many materials in various conditions are reported in References 1 through 16.

9.2 *Calculation of the plastic-depth associated with each cycle in a Multi-Cycle ABI test*—Linear regression analysis is performed on the data of each elastic partial unloading, and the calculated slope is extrapolated where its intersection with the depth axis determines the plastic depth associated with the upper force of the cycle. This is shown schematically in Fig. 1a and graphically (from an example ABI test data using a 0.762-mm diameter indenter) in Fig. 5.

9.3 *Calculation of true-stress and true-plastic-strain pairs*—The incremental values of the true-stress versus true-plastic-strain curve are calculated from Equations 1 through 11**(3)**. For a single-cycle ABI test, the plastic chordal diameter is replaced by the total chordal diameter (calculated from the total depth, Equation 9). It is important to note that these equations are independent of the work-hardening behavior of the material (i.e., regardless if it follows a power law or not).

9.4 *Calculation of the ABI-derived yield strength*—The yield strength determined from an ABI test is calculated from Equations 9 through 11 **(3)**. Figure 6 is an example plot of Equation 10. The values of the yield strength slope and the yield strength offset (B) depend on the class of metal and the indenter diameter. These values are empirically determined to be in close agreement with the 0.2% offset yield strength determined from uniaxial tensile tests **(16)**. For example, a recommended value for the yield strength slope (β_m) for carbon steel testing using a 0.762-mm tungsten carbide indenter is 0.22. The values of the yield parameter (A), yield strength slope (β_m), and yield strength offset (B) used in the ABI-derived yield strength calculation shall be documented in the ABI test report.

9.5 *Calculation of strain-hardening exponent (n), strength coefficient (K), Lüders strain (ε_L), and estimated ultimate tensile strength (UTS)*—The true-stress versus true-plastic-strain results from the ABI test are fitted to the power law form of Equation 12 as described in Method E 646. A single power curve is fitted to the entire curve between yield and the final true strain at the end of the test, or the yield strength point can be eliminated from the data fit, depending on the desired strain range for determining the n value. The strain-hardening exponent (n) and the strength coefficient (K) are determined from this empirical representation of the flow curve (Equation 12). An example of ABI-measured flow properties, including the yield strength value, and their power-law fitting is shown in Fig. 7. The Lüders strain is calculated from Equation 13. If the flow properties of the test material are well represented by the power law form of Equation 12 (E 646), then the ultimate tensile strength can be estimated from Equation 14. If the ABI-measured true-stress versus true-plastic-strain curve does not follow a single power law, then it must be calculated from the plot of true-stress versus engineering strain as explained in item 9.6 below and in Figure 8.

NOTE 2—In the ABI test there is no necking behavior similar to that occurring in a tensile test. Hence the *UTS* can be estimated from Equation 14 or it can be calculated using the plot of true-stress versus engineering strain.

9.6 *Calculation of uniform ductility and ultimate tensile strength (UTS)*— A straight line is drawn from an engineering strain value of –1.00 to be a tangent to the true-stress versus engineering strain curve **(17)**. The X-axis value of this line at the tangent intersection point determines the uniform ductility while the intersection of the line with the Y-axis, at the origin (0,0), determines the engineering *UTS* value. An example of the calculation of the Uniform Ductility and the Engineering *UTS* from the ABI-measured True-Stress versus Engineering Strain curve is shown in Figure 8.

9.7 *Indenter Diameter Selection and Data Qualification*—The indenter diameter is selected based on the test volume (thickness, final indentation depth, and available test area) and the grain size of the metal. For a Single-Cycle test, some of the force-depth data collected at very low depth (the first 5% depth of the entire test) must be excluded from the stress-strain curve calculations if the indentation chordal diameter at such a small depth covers less than five grains. Notice that the progressive ball indentation at lowest practical depth increment should cover more than five grains in order to obtain macroscopic stress-strain properties. An example comparison between a small indentation (made using a 0.254-mm diameter indenter and a force of 2 N) and the grain size of the test material is provided in Figure 9. An example of qualified ABI force-depth data (generated using a 0.508-mm diameter indenter), test results, and comparison with tensile test results are shown in Fig. 10. An example of the geometry of a large indenter (1.575-mm diameter) is shown also in Figure 10 (inset photo).

$$\in_p = \frac{0.2 d_p}{D} \tag{1}$$

Where:

ϵ_p = true plastic strain,

d_p = plastic indentation diameter,

D = diameter of the ball indenter.

$$\sigma_t = \frac{4P}{\pi d_p^2 \delta} \tag{2}$$

Where:

σ_t = true stress,

P = applied indentation force,

δ = a parameter whose value depends on the stage of development of the plastic zone beneath the indenter as shown in Equation 5 below.

$$d_p = \left\{ 0.5CD \left[\frac{h_p^2 + \left(\frac{d_p}{2}\right)^2}{h_p^2 + \left(\frac{d_p}{2}\right)^2 - h_p D} \right] \right\}^{1/3} \tag{3}$$

Where h_p is the plastic indentation depth and “C” is defined in Equation 4 below.

$$C = 5.47P\left(\frac{1}{E_1} + \frac{1}{E_2}\right) \tag{4}$$

Where E1 and E2 are the elastic moduli of the indenter and the test sample, respectively.

$$\delta = \left\{ \begin{array}{ll} 1.12 & \Phi \le 1 \\ 1.12 + \tau \ln \Phi & 1 < \Phi \le 27 \\ \delta_{\max} & \Phi > 27 \end{array} \right| \tag{5}$$

$$\delta_{\max} = 2.87\alpha_m \tag{6}$$

Where α_m is the constraint factor index.

$$\Phi = \frac{\in_p \ E_2}{0.43\sigma_t} \tag{7}$$

$$\tau = \frac{\delta_{\max} - 1.12}{\ell n(27)} \tag{8}$$

Where "ℓn" is the natural logarithm.

$$d_t = 2\sqrt{h_t D - h_t^2} \tag{9}$$

Where h_t and d_t are the total indentation depth and total indentation diameter while the force is being applied, respectively.

$$\frac{P}{d_t^2} = A\left(\frac{d_t}{D}\right)^{m-2} \tag{10}$$

Where A is the material yield parameter and m is Meyer's index.

$$\sigma_y = \beta_m * A + B \tag{11}$$

Where σ_y is the ABI-determined yield strength, β_m is the material yield slope, and B is the yield-strength offset-constant.

$$\sigma_t = K \in_p^n \tag{12}$$

Where K is the strength coefficient and n is the strain-hardening exponent.

$$\ell n\left(\frac{K}{\sigma_y}\right) = \in_L - n * \ell n \in_L \tag{13}$$

Where ϵ_L is Lüders strain.

$$UTS = K\left(\frac{n}{e}\right)^n \tag{14}$$

Where UTS is the ABI-estimated ultimate tensile strength and e = 2.718.

10. Report

10.1 A recommended format for reporting the test parameters, equipment parameters, analysis parameters, and test results for both Multi-Cycle and Single-Cycle ABI tests is shown in Fig. 11 (a) while an additional reporting format suggested for the Multi-Cycle ABI test only is shown in Fig. 11(b).

10.2 Report the following information for each ABI test: test name, test material and test number, test atmosphere, test temperature, indenter diameter, indenter speed, number of unloadings, data acquisition rate, percentage of the partial unloading, maximum indentation depth (percentage of indenter radius used in final indentation), indenter material and its elastic modulus, constraint factor, yield strength slope and offset, total number of data points collected, reporting of any force or depth limits triggered during the ABI test, ABI results of yield strength, strain-hardening exponent, strength coefficient, estimated engineering *UTS*, calculated engineering *UTS* (from the plot of true-stress versus engineering strain), and calculated uniform ductility.

10.3 Report the additional data and test results for each cycle of a Multi-Cycle ABI test: cycle number, maximum total depth, plastic depth, maximum force, plastic indentation chordal diameter, unloading slope, R^2 value (regression coefficient) for the regression analysis of the partial unloading slope, total chordal diameter, true-plastic-strain, and true-stress.

10.4 Report the following graphs: force-depth data before and after adjustment for the depth associated with the applied preload, yield strength calculation plot, true-stress versus true-plastic-strain curve with individual points and power-law fit, and a plot of the true-stress versus engineering strain.

11. Precision and Bias

11.1 *Precision*—The precision of any of the various ABI-determined flow properties cited in these test methods is a function of the precision and bias of the various measurements of indenter diameter, the precision and bias of the depth measurement, the precision and bias of the force measurement, and the precision and bias of the data acquisition system used to construct the force-depth curve. It is not possible to make meaningful statements concerning the precision and bias for all these measurements. However it is possible to derive useful information concerning the precision of the ABI-measured flow properties in a global sense from interlaboratory test programs. Values of the ABI-determined yield strength and true-stress versus true-plastic-strain curves were evaluated in **(15)** for several pressure vessel steels at various test temperatures. The ABI-derived yield strength and estimated ultimate strength values were evaluated in **(16)** for seven pipeline steels, with various grades and manufacturing dates, tested at room temperature using two indenter diameters (0.508 mm and 0.762 mm), and the ABI test results were compared to the results from tensile tests on the same materials.

An interlaboratory test program[4] gave the following values for the coefficients of variation for the most commonly ABI-measured flow properties:

Coefficient of Variation, %

	ABI-Yield Strength	ABI-Estimated Ultimate Strength	Strength Coefficient	Strength-Hardening Exponent	Uniform Ductility
CV $\%_r$	1.4	1.5	2.6	5.8	6.9
CV $\%_R$	1.7	2.3	3.4	6.7	7.8

CV $\%_r$ = repeatability coefficient of variation in percent within a laboratory
CV $\%_R$ = repeatability coefficient of variation in percent between laboratories

11.1.1 The values shown are the averages from ABI tests on four frequently tested metals (ferrous and non-ferrous), selected to include most of the normal range for each property listed above. The slightly higher coefficients of variation for the strain-hardening exponent and the uniform ductility are due to the fact that these two properties depend on the shape of the stress-strain curve and the homogeneity of the metal. The values of the coefficient of variation are provided to allow potential users of these test methods to assess, in general terms, their usefulness for a proposed application.

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[4] Supporting data are available from ASTM Headquarters. Request RR: E28-XXXX.

11.2 *Bias*—The procedures in the ABI test methods for measuring flow properties have no bias because these properties can be defined only in terms of the test methods.

12. Calibration and Standardization

12.1 The following devices should be calibrated against standards traced to national standards (in the United States, National Institute of Standards and Technology). Applicable ASTM methods are listed beside the device.

Force-measuring system	(load cell)	E 4 and E 74
Micrometers (for calibrating the LVDT)		

12.2 Calibrations should be as frequent as is necessary to assure that the errors in all tests do not exceed the permissible variations listed in these test methods. The maximum period between calibrations of the load cell and the LVDT should be two years.

13. Keywords

13.1 Automated Ball Indentation, ball indenter, indenter velocity, force-depth data, partial unloading slope, yield parameter, yield strength, true-stress, true-plastic-strain, strain-hardening exponent, strength coefficient, ultimate strength, uniform ductility, Lüders strain

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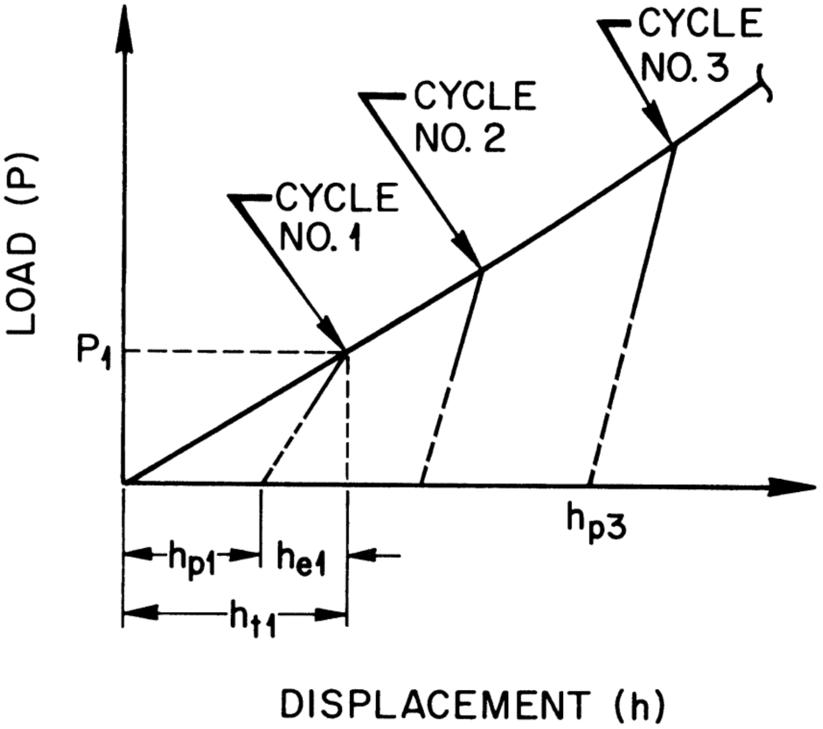
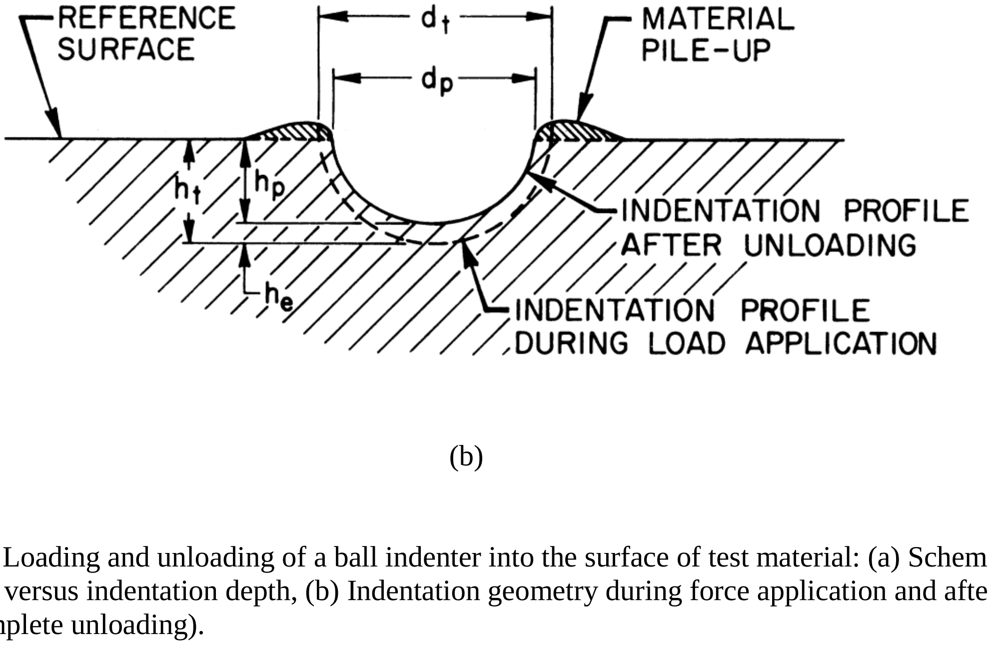


(a)



(b)

Fig. 1 Cyclic Loading and unloading of a ball indenter into the surface of test material: (a) Schematic of applied force versus indentation depth, (b) Indentation geometry during force application and after force removal (complete unloading).

Fig. 2 Example of raw data collected using a 0.762-mm diameter tungsten carbide indenter on a ferritic steel sample. Note that a zero value is temporarily assumed for the indentation depth associated with the preload value of the ABI test. The actual indentation depth value associated with the preload value is calculated next in Fig. 3.

Fig. 3 Example of the linear regression of the force-depth data from the first loading cycle of the Multi-Cycle ABI test shown in Fig. 2. The solid line resulting from the linear regression is used to calculate the indentation depth associated with the indentation preload value (the intersection value of the X-axis).

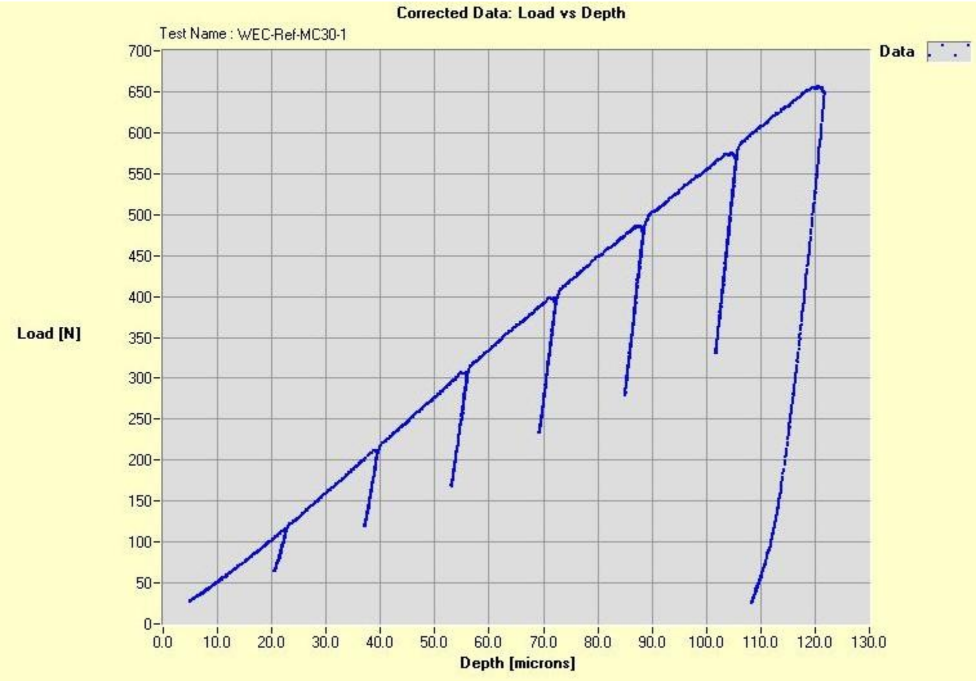


Fig. 4 Example of the corrected ABI data (after shifting the curve to the right by the amount of indentation depth associated with the indentation preload calculated in Fig. 3).

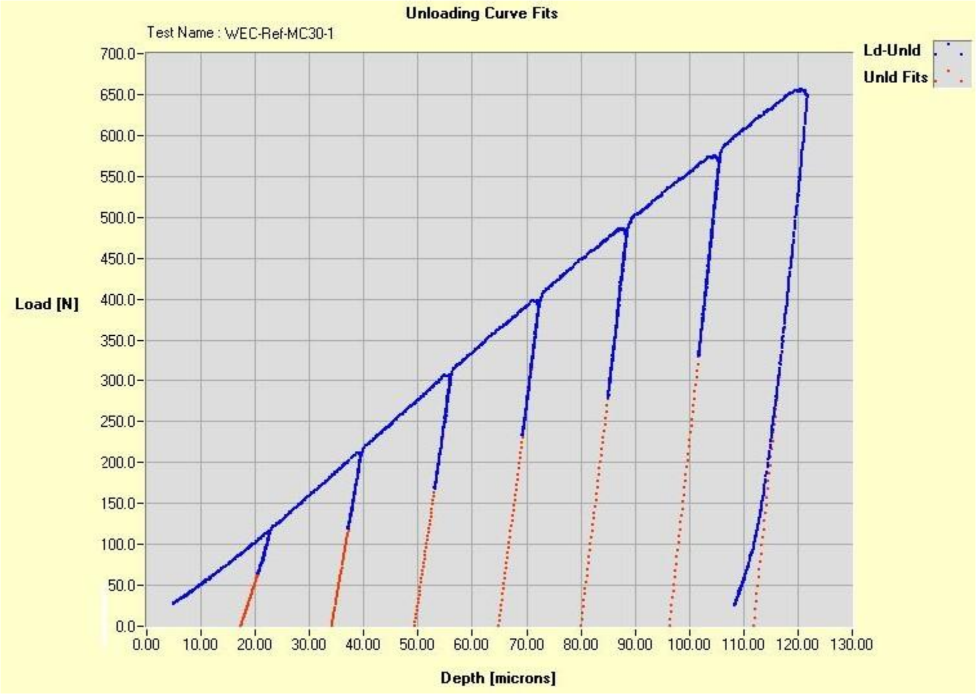


Fig. 5 Example of the corrected force-depth data showing the linear regression of the elastic unloadings (dotted lines). The intersection of the dotted lines (extrapolated from the unloadings) with the X-axis determines the plastic-depth associated with each cycle.

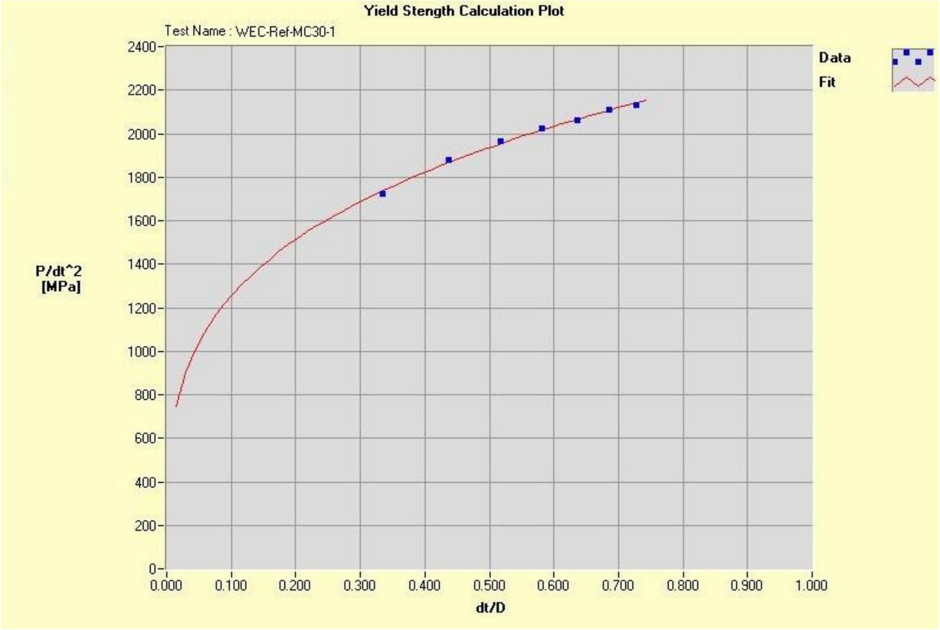


Fig. 6 Yield strength calculation plot. The extrapolation of the curve to an X-axis value of 1.00 produces the yield strength parameter "A" that is used in Equation (11) to calculate the yield strength value.

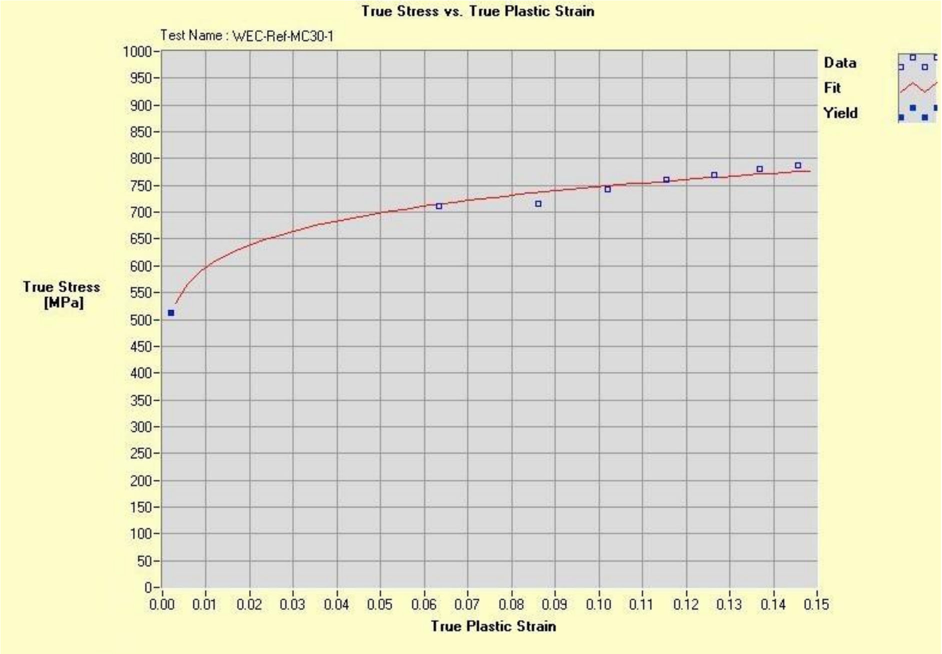


Fig. 7 Example of the true-stress versus true-plastic-strain curve determined from the ABI test. The yield strength is plotted with a different symbol (solid square instead of an open square) since it is calculated from the plot of Fig. 6 and it is not a back-extrapolation from the other points. The solid line is calculated from the power-law fitting of the data as described in ASTM Standard E646.

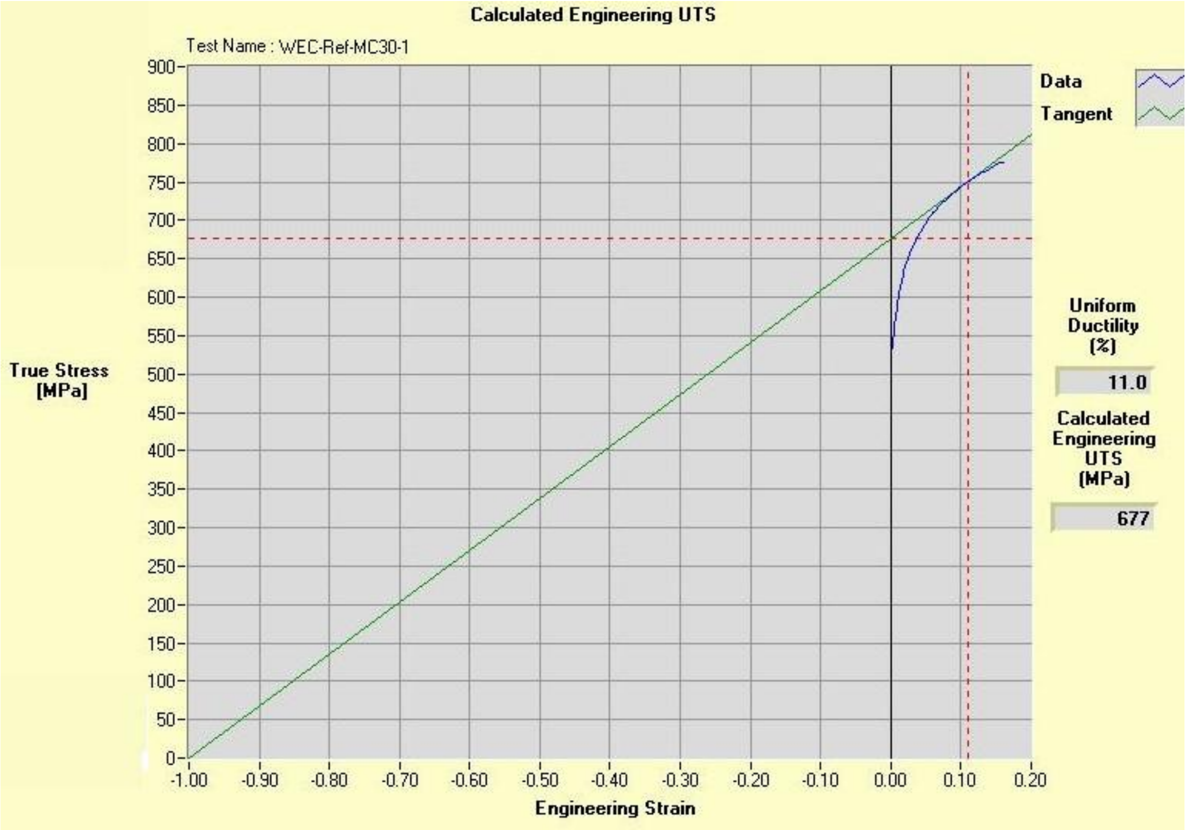


Fig. 8 Example of the calculation of the Uniform Ductility and the Engineering Ultimate Tensile Strength (*UTS*) from the ABI-measured True-Stress versus Engineering Strain curve.

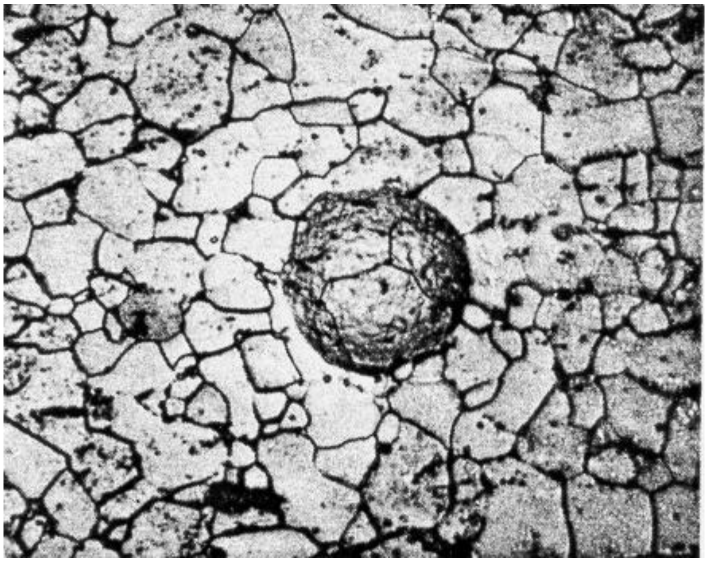


Fig. 9 Spherical indent in 1015 steel (20 µm grain size) obtained at a force of 2 N using a 254 µm (0.010 in) diameter indenter. Notice that the progressive ball indentation at lowest depth increment should cover more than five grains in order to obtain macroscopic stress-strain properties.

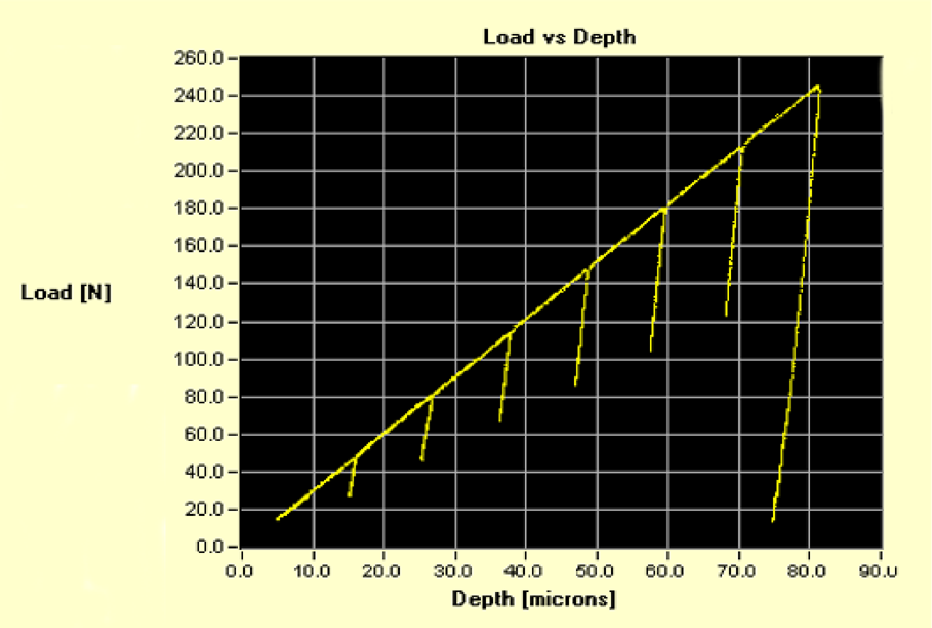


Fig. 10 (a) Indentation force versus depth in an ABI test using a 0.508-mm (0.020-in) diameter tungsten carbide indenter on a ferritic steel material.

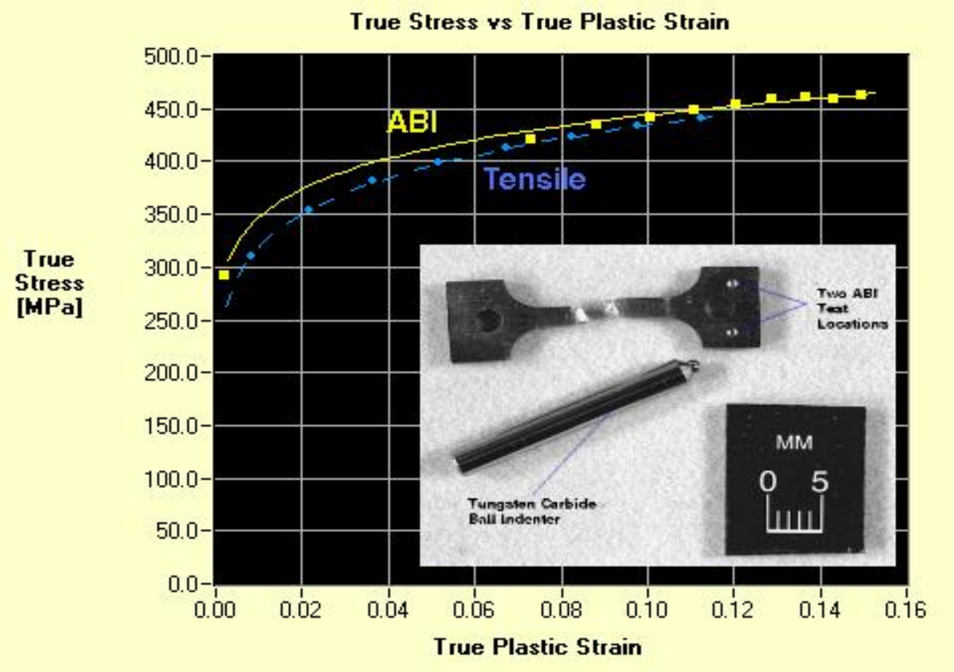
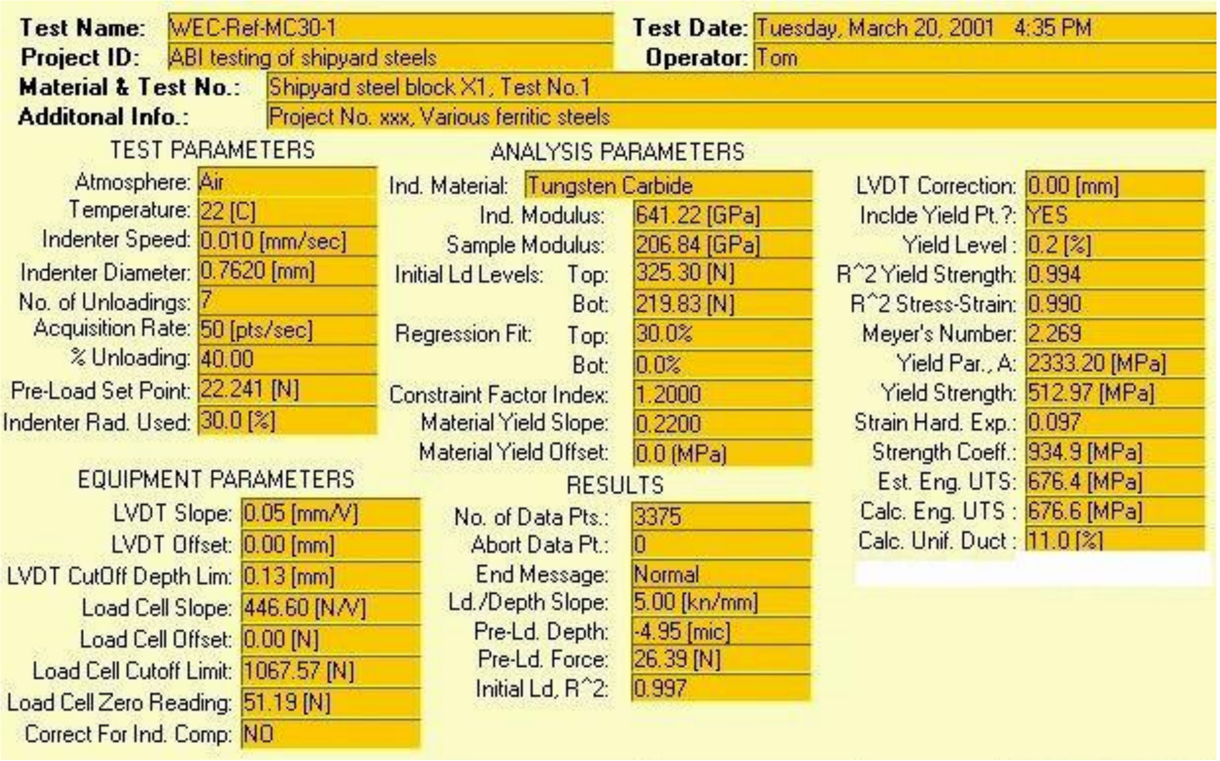


Fig. 10 (b) True-stress versus true-plastic-strain curves from ABI (using a 0.508-mm diameter indenter, data shown in Fig. 10a) and tensile tests on a ferritic steel. A miniature tensile specimen is shown in the inset photo with two indentations made with a larger indenter (1.575-mm diameter).



Test Name: WEC-Ref-MC30-1

Test Date: Tuesday, March 20, 2001 4:35 PM

Project ID: ABI testing of shipyard steels

Operator: Tom

Material & Test No.: Shipyard steel block X1, Test No.1

Additonal Info.: Project No. xxx, Various ferritic steels

TEST PARAMETERS

Atmosphere: Air
Temperature: 22 [C]
Indenter Speed: 0.010 [mm/sec]
Indenter Diameter: 0.7620 [mm]
No. of Unloadings: 7
Acquisition Rate: 50 [pts/sec]
% Unloading: 40.00
Pre-Load Set Point: 22.241 [N]
Indenter Rad. Used: 30.0 [%]

EQUIPMENT PARAMETERS

LVDT Slope: 0.05 [mm/V]
LVDT Offset: 0.00 [mm]
LVDT CutOff Depth Lim: 0.13 [mm]
Load Cell Slope: 446.60 [N/V]
Load Cell Offset: 0.00 [N]
Load Cell Cutoff Limit: 1067.57 [N]
Load Cell Zero Reading: 51.19 [N]
Correct For Ind. Comp: NO

ANALYSIS PARAMETERS

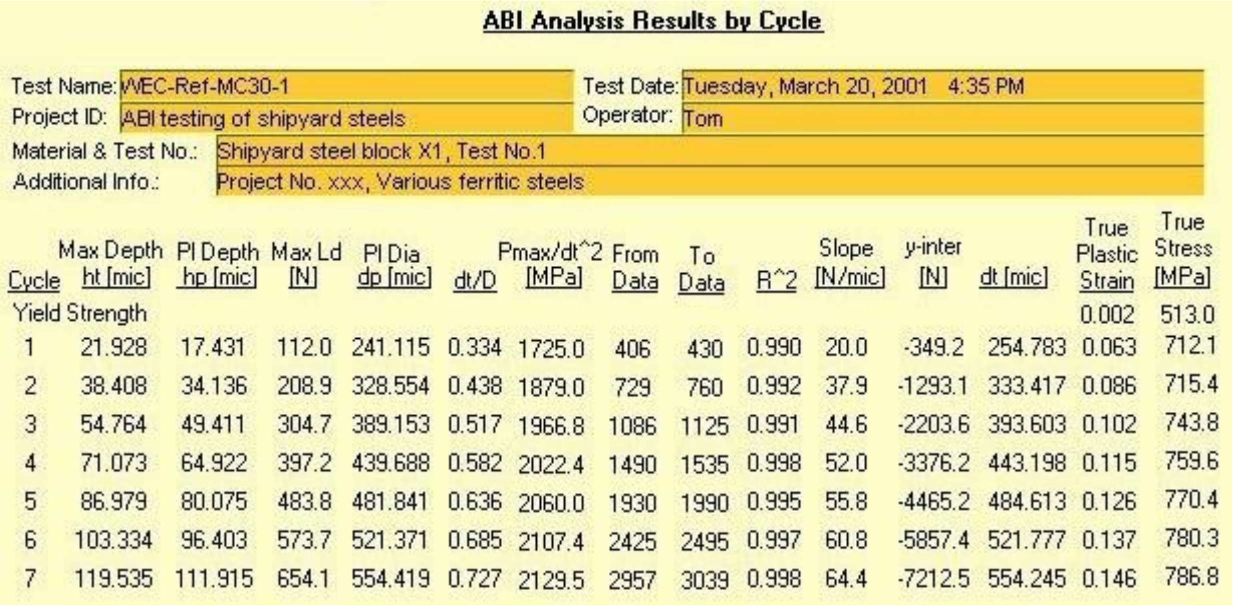
Ind. Material: Tungsten Carbide
Ind. Modulus: 641.22 [GPa]
Sample Modulus: 206.84 [GPa]
Initial Ld Levels: Top: 325.30 [N]
Bot: 219.83 [N]
Regression Fit: Top: 30.0%
Bot: 0.0%
Constraint Factor Index: 1.2000
Material Yield Slope: 0.2200
Material Yield Offset: 0.0 (MPa)

RESULTS

No. of Data Pts.: 3375
Abort Data Pt.: 0
End Message: Normal
Ld./Depth Slope: 5.00 [kn/mm]
Pre-Ld. Depth: -4.95 [mic]
Pre-Ld. Force: 26.39 [N]
Initial Ld, R^2: 0.997

LVDT Correction: 0.00 [mm]
Inclde Yield Pt.?: YES
Yield Level : 0.2 [%]
R^2 Yield Strength: 0.994
R^2 Stress-Strain: 0.990
Meyer's Number: 2.269
Yield Par., A: 2333.20 [MPa]
Yield Strength: 512.97 [MPa]
Strain Hard. Exp.: 0.097
Strength Coeff.: 934.9 [MPa]
Est. Eng. UTS: 676.4 [MPa]
Calc. Eng. UTS : 676.6 [MPa]
Calc. Unif. Duct : 11.0 [%]

Fig. 11 (a) Suggested data reporting format for both Multi-Cycle and Single-Cycle ABI tests. Example of the first page of the ABI test report including the test parameters, equipment parameters, analysis parameters, and the test results.



ABI Analysis Results by Cycle

Test Name: WEC-Ref-MC30-1

Test Date: Tuesday, March 20, 2001 4:35 PM

Project ID: ABI testing of shipyard steels

Operator: Tom

Material & Test No.: Shipyard steel block X1, Test No.1

Additional Info.: Project No. xxx, Various ferritic steels

Cycle	Max Depth ht [mic]	Pl Depth hp [mic]	Max Ld [N]	Pl Dia dp [mic]	dt/D	Pmax/dt^2 [MPa]	From Data	To Data	R^2	Slope [N/mic]	y-inter [N]	dt [mic]	True Plastic Strain	True Stress [MPa]
Yield Strength													0.002	513.0
1	21.928	17.431	112.0	241.115	0.334	1725.0	406	430	0.990	20.0	-349.2	254.783	0.063	712.1
2	38.408	34.136	208.9	328.554	0.438	1879.0	729	760	0.992	37.9	-1293.1	333.417	0.086	715.4
3	54.764	49.411	304.7	389.153	0.517	1966.8	1086	1125	0.991	44.6	-2203.6	393.603	0.102	743.8
4	71.073	64.922	397.2	439.688	0.582	2022.4	1490	1535	0.998	52.0	-3376.2	443.198	0.115	759.6
5	86.979	80.075	483.8	481.841	0.636	2060.0	1930	1990	0.995	55.8	-4465.2	484.613	0.126	770.4
6	103.334	96.403	573.7	521.371	0.685	2107.4	2425	2495	0.997	60.8	-5857.4	521.777	0.137	780.3
7	119.535	111.915	654.1	554.419	0.727	2129.5	2957	3039	0.998	64.4	-7212.5	554.245	0.146	786.8

Fig 11 (b) Suggested data reporting format for the Multi-Cycle ABI test. Example of the second page of the ABI test report including the tabulated values of the true-plastic-strain versus the true-stress data pairs from all cycles.