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Ultrasonic Attenuation Coefficient Determination and
Probability of Sizing Analysis

Structural Integrity & Materials Evaluation

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1 Abstract

This paper is split into two parts. Part one covers the findings of an experiment carried out using an ultrasonic flaw detector on two material samples to detect defects and then calculate the attenuation coefficient values for each sample. Part two of the paper covers analysing through wall thickness measurements of 10 different operators on 21 material defects. The dataset was analysed, and various plots were generated using Microsoft Excel to evaluate the accuracy of the measurements that the operators had taken.

Various statistical analysis techniques were used, including linear regression, standard deviation, and standard error.

2 Apparatus

2.1 Part one

Part 1 of the report required an experiment to be carried out. To complete ultrasonic testing on two samples, the following apparatus was used:

- Silverwing D-Scan 705 digital ultrasonic flaw detector
- Zero-degree 5MHz, single-crystal probe
- A mild steel rectangular block
- Brake disc
- Tissue
- Ultrasonic coupling gel
- Scientific calculator
- Notebook

3 Introduction and Method

This scientific report has been split across two parts. Part one covers the use of TOFD (Time-of-Flight Diffraction) methods to establish material attenuation coefficient values for two samples. Part two of the report covers statistical analysis of through wall thickness measurements taken by 10 different operators, to determine the accuracy of the accuracy of the operator measurements and processes in general.

3.1 Part one

The following steps outline the method that contributed toward part one of the assignment.

1. Gather all apparatus as listed on page 2 of this report. Ensured all equipment was in good working order and that the single crystal probe wasn't damaged in any way, this could have affected accuracy of the experiment.
2. Turned on the ultrasonic flaw detector and ensured that it was in single line mode and not double. This could be easily switched by pressing the single/double button on face of the flaw detector.
3. Then checked that the flaw detector has been calibrated to zero, the velocity input had been set to a suitable value based on the Ultrasound - Material Properties PDF [1], which in this case was mild steel at 5.96×10^3 m/s. For the purposes of this experiment, range was adjusted to 70, this was to allow three backwall echoes to be observed on the flaw detector.
4. Delay was set to zero, due to there being no delay line being used for this experiment.

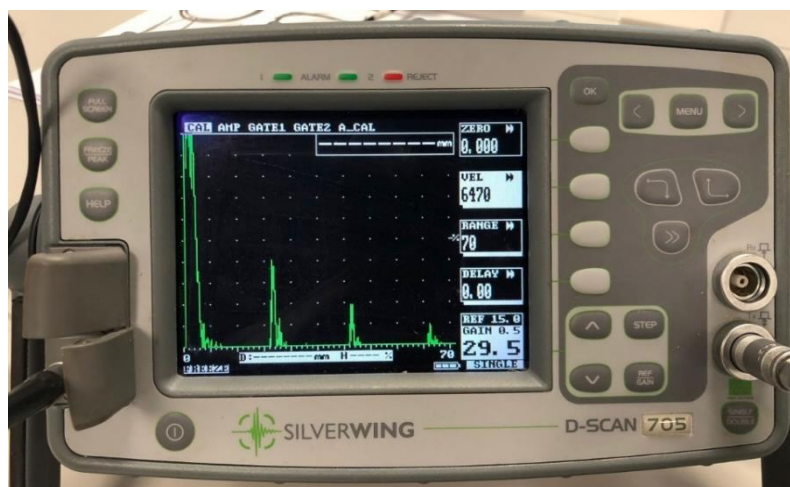


Figure 1- Silverwing D-Scan 705 digital ultrasonic flaw detector.

5. The mild steel rectangular block was examined first. It measured 82mm long so it was decided that it would be examined at roughly 20mm increments along its length to gain an even spread of data.

6. A fair amount of coupling gel, enough to lightly cover the entire top face of the sample was applied. It is important that there is couplant between the end of the probe and the sample to match the acoustic impedance of the probe to the sample, therefore maximising energy transfer. It was important not to drag the probe along the face of the sample, as the probe didn't have a wear face, the crystal would wear away at significant speed.



Figure 2- Mild steel rectangular block sample with coupling gel applied.

7. By pressing the probe end to the face of the sample, the flaw detector displayed three backwall echoes as specified by the range value. By adjusting the gain (+ or -), it was possible to manipulate the backwall echoes so that they fit within the scale shown on the flaw detector. When a suitable reading was displayed, the freeze button was used to freeze the reading to the screen, so that those results could be recorded.
8. Once all readings had been taken for each desired position on the sample, it could then be wiped clean with tissue to remove any excess coupling gel, this sample was then complete.
9. This process was repeated with the brake disc sample, measuring 4 positions on the main face of the brake disc, and 4 positions on the mounting part of the brake disc. Therefore 8 positions total were tested, and the results recorded for further use.



Figure 3 - Brake disc sample

3.2 Part two

Using linear regression and statistical analysis techniques through Microsoft Excel, it was possible to evaluate the accuracy of each operator and through wall thickness results. Linear regression can be used to predict a certain variable based on another variable [2]. Scatter plots could be generated with a trend line which would clearly show how results varied to the general data trend.

4 Measurements and Results

4.1 Part one

Before the experiment could begin, it was necessary to measure both samples and take note of their dimensions. The mild steel rectangular block was 82mm in length and 19mm in thickness. The main face of the brake disc measured 12.5mm in thickness, and the mounting face was 8.5mm in thickness.

Throughout the experiment, results were written into a notebook so that they could be later inserted into Microsoft Excel for calculation and analysis. These raw results can be observed below.

MILD Steel BAR				B ₂ /B ₁ 2x	B ₃ /B ₂ 2x	B ₃ /B ₁ 4x
Position (mm)	B ₁	B ₂	B ₃	α_{DBmm1}	α_{DBmm2}	α_{DBmm3}
20mm	83	49	32	-0.12	-0.10	-0.11
40mm	78	39	22	-0.15	-0.13	-0.14
60mm	70	35	20	-0.16	-0.13	-0.14
80mm	72	36	20	-0.16	-0.13	-0.15
80mm	55	30	14	-0.14	-0.17	-0.16

Figure 4 - Mild steel rectangular block raw results

Disc Brake				2/B ₁ 2x	B ₃ /B ₂ 2x	B ₃ /B ₁ 4x
Position	B ₁	B ₂	B ₃	α_{DBmm1}	α_{DBmm2}	α_{DBmm3}
A	72	20	6	-0.45	~~-0.42~~ ~~-0.36~~	-0.43
B	70	15	4	-0.54	-0.46	-0.50
C	59	15	4	-0.48	-0.46	-0.47
D	45	10	3	-0.52	-0.42	-0.47
* E	79	34	15	~~0.43~~ ~~-0.45~~	-0.42	-0.42
* F	77	32	13	-0.45	-0.46	-0.45
* G	70	32	18	-0.40	-0.30	-0.35
* H	63	30	15	-0.38	-0.35	-0.37

Figure 5 - Disc brake raw results

As figures four and five show, handwritten calculations were completed to gain an immediate set of results. This would also allow for validation against Microsoft Excel calculations when required.

A wave is transmitted from the end of the single crystal probe. This wave passes through the test sample until it reaches a boundary (back wall of the sample). At this point the wave heads back toward its source. This process continues, however each time the wave bounces off a backwall, its trajectory widens slightly. In other words, transmission becomes less accurate each time it hits a boundary.

Discontinuities that occur closer in the material to the probe are shown prior to discontinuities that occur further away from the probe. [3]

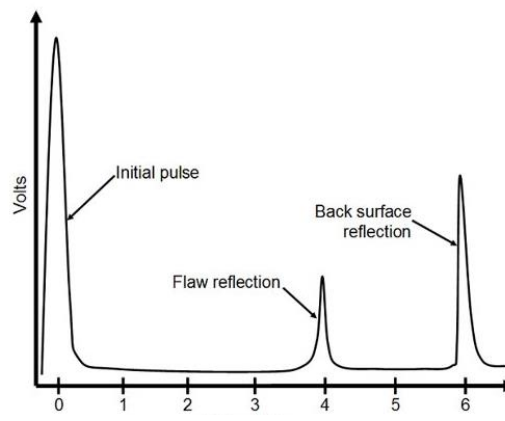


Figure 6 - Time of Flight Diffraction example.

4.2 Part Two

To analyse each operator and their results, a table of raw data was provided that was used within Microsoft Excel. This raw data table can be seen below.

Defect	true size	Op1	Op2	Op3	Op4	Op5	Op6	Op7	Op8	Op9	Op10
A	0.25	0.50	0.50	0.00	1.00	0.00	0.50	0.50	0.80	1.00	0.30
B	0.27	0.73	1.20	0.50	1.00	0.00	1.00	0.50	0.80	1.00	1.20
C	0.28	0.76	1.00	1.20	1.00	0.00	0.50	0.50	1.30	1.00	0.70
D	0.40	0.91	0.50	1.00	1.20	1.00	1.00	0.60	1.50	1.00	0.80
E	0.40	0.98	1.20	1.00	1.40	1.00	1.10	0.20	1.60	1.00	0.90
F	0.50	0.79	0.90	1.00	1.10	1.00	0.80	0.00	1.00	1.20	0.50
G	0.52	1.01	1.50	1.10	0.90	1.50	1.00	1.00	0.90	1.00	0.70
H	0.55	0.96	1.20	0.80	0.50	0.90	1.20	1.30	1.60	1.00	0.40
I	0.70	1.35	1.50	0.90	2.00	1.60	1.20	1.60	2.20	1.00	1.00
J	0.98	1.31	1.00	0.80	1.90	2.00	1.60	0.50	1.80	1.00	1.40
K	1.12	1.37	0.50	1.00	1.00	1.80	1.80	1.80	2.00	1.50	1.30
L	1.15	1.56	1.80	1.30	2.20	1.00	1.50	1.80	2.00	1.50	1.20
M	1.10	1.60	2.00	1.40	2.00	1.60	1.50	0.50	2.20	2.00	1.60
N	1.30	1.73	2.10	0.90	2.20	2.00	2.00	1.70	2.00	1.50	1.70
O	1.60	1.56	0.80	0.90	2.00	2.00	1.50	1.20	2.00	2.00	1.50
P	1.80	2.14	2.00	1.40	2.40	2.00	3.20	2.20	2.50	2.50	1.10
Q	2.10	2.49	1.80	2.30	3.50	2.50	3.00	2.00	3.20	2.00	2.60
R	2.70	2.97	3.00	3.20	2.80	2.50	3.50	2.50	3.50	3.50	2.20
S	4.90	4.87	4.50	4.50	5.70	4.50	4.40	4.20	5.40	5.50	5.50
T	6.00	6.17	5.50	6.20	7.00	6.50	5.50	5.30	6.70	6.50	6.00
U	7.50	6.99	6.00	6.25	8.00	7.20	6.50	6.50	6.90	8.00	6.50

Figure 7 - Raw data relevant to through wall thickness measurements [3].

Using the data shown in figure 7, statistical analysis techniques were used to analyse the accuracy of each operator. This allowed various conclusions and predictions to be made based on the existing data.

5 Calculations and Error Estimates

5.1 Part One

The attenuation coefficient refers to how easily a material could be penetrated by an energy beam. In the case of this report, ultrasound will be the energy beam [4]. The attenuation coefficient is labelled as α and is measured in dB/mm (Decibel per millimetre) [5].

$$\alpha = \frac{20}{dist} \times \log_{10}\left(\frac{B}{b}\right)$$

Equation 1 - Material attenuation coefficient value equation.

Where:

α = Attenuation coefficient

dist = Sample thickness measured in millimetres

B = Backwall value number one

b = Backwall value number two

As shown above, the equation used to calculate attenuation coefficient values for both samples utilises two backwall values taken from the flaw detector display. 'Backwall value number one' and 'Backwall value number two' refer to B1, B2, and B3 values shown in figures 4 and 5. For ease of showing this equation, letters B and b were used to identify these values.

Depending on whether Dbmm1, Dbmm2, or Dbmm3 was being calculated would determine which values for B and b would be used in equation 1.

The following equation has been included as a sample calculation using equation 1 to outline the process undertaken to obtain attenuation coefficient values for both material samples.

$$Dbmm1 = \left(\frac{20}{(19 \times 2)}\right) \times \left(\log_{10}\left(\frac{49}{83}\right)\right)$$

Equation 2 - Sample calculation of Dbmm1 for mild steel bar material sample.

Equation 2 returned an attenuation coefficient of $\alpha = -0.12$ Db/mm. The equation shows that distance has been multiplied by two. This is because the distance between backwall echoes 1 and 2 is simply two times the thickness of the material sample. When Dbmm3 was calculated, it was important to remember that the distance should be multiplied by four, as it was B3/B1 (B meaning Backwall) which is double the distance between backwall echo 1 and 3.

Mild Steel Bar								
	B1	B2	B3	B2/B1 2x	B3/B2 2x	B3/B1 4x		
Position (mm)				α DBmm1	α DBmm2	α DBmm3	Mean α DBmm	Std Deviation
0	83	49	32	-0.12	-0.10	-0.11	-0.11	0.01
20	78	39	22	-0.16	-0.13	-0.14	-0.14	0.01
40	70	35	20	-0.16	-0.13	-0.14	-0.14	0.02
60	72	36	20	-0.16	-0.13	-0.15	-0.15	0.01
80	55	30	14	-0.14	-0.17	-0.16	-0.16	0.02
Average							-0.14	0.01
MIN							-0.20	
MAX							-0.08	

Figure 8 - Mild steel bar sample calculations and results incorporated to Microsoft Excel.

Brake Disc								
				B2/B1 2x	B3/B2 2x	B3/B1 4x		
Position (mm)	B1	B2	B3	α DBmm1	α DBmm2	α DBmm3	Mean α DBmm	Std Deviation
A	72	20	6	-0.45	-0.42	-0.43	-0.43	0.01
B	70	15	4	-0.54	-0.46	-0.50	-0.50	0.04
C	59	15	4	-0.48	-0.46	-0.47	-0.47	0.01
D	45	10	3	-0.52	-0.42	-0.47	-0.47	0.05
Average							-0.47	0.03
MIN							-0.58	
MAX							-0.35	
E	79	34	15	-0.43	-0.42	-0.42	-0.42	0.01
F	77	32	13	-0.45	-0.46	-0.45	-0.45	0.01
G	70	32	18	-0.40	-0.29	-0.35	-0.35	0.05
H	63	30	15	-0.38	-0.35	-0.37	-0.37	0.01
Average							-0.40	0.02
MIN							-0.48	
MAX							-0.32	

Figure 9 - Brake disc sample calculations and results incorporated to Microsoft Excel.

To produce a plot in Excel that would outline display the results generated, it was necessary to calculate a range of mean values which could then also be used to calculate standard deviation. It was useful to have standard deviation values as it is useful to analyse the spread of the dataset [6].

Normal distribution curves were generated to analyse the results. The peak of these plots represents mean values, and data displayed either side of the mean showed how far from the mean those results were. A normal distribution function in Microsoft Excel was used to calculate these data points that would eventually be used to generate the plots.

MILD Steel Bar	
X Norm Dist	Y Norm Dist
-0.20	0.01
-0.19	0.13
-0.18	1.01
-0.17	4.92
-0.16	14.43
-0.15	25.57
-0.14	27.38
-0.13	17.73
-0.12	6.93
-0.11	1.64
-0.10	0.23
-0.09	0.02
-0.08	0.00

Figure 10 - Mild steel bar normal distribution raw data.

Brake Disc Main	
X Norm Dist	Y Norm Dist
-0.58	0.00
-0.57	0.02
-0.56	0.06
-0.55	0.20
-0.54	0.53
-0.53	1.24
-0.52	2.56
-0.51	4.67
-0.50	7.48
-0.49	10.53
-0.48	13.06
-0.47	14.25
-0.46	13.67
-0.45	11.54
-0.44	8.58
-0.43	5.60
-0.42	3.22
-0.41	1.63
-0.40	0.73
-0.39	0.28
-0.38	0.10
-0.37	0.03
-0.36	0.01
-0.35	0.00

Figure 11 - Brake disc main face normal distribution raw data.

Brake Disc Mount	
X Norm Dist	Y Norm Dist
-0.48	0.01
-0.47	0.05
-0.46	0.25
-0.45	1.01
-0.44	3.15
-0.43	7.48
-0.42	13.64
-0.41	19.06
-0.40	20.41
-0.39	16.76
-0.38	10.55
-0.37	5.09
-0.36	1.88
-0.35	0.53
-0.34	0.12
-0.33	0.02
-0.32	0.00

Figure 12 - Brake disc mount face normal distribution raw data.

Raw data shown in figures 10, 11, and 12 was used to generate the following normal distribution plots.

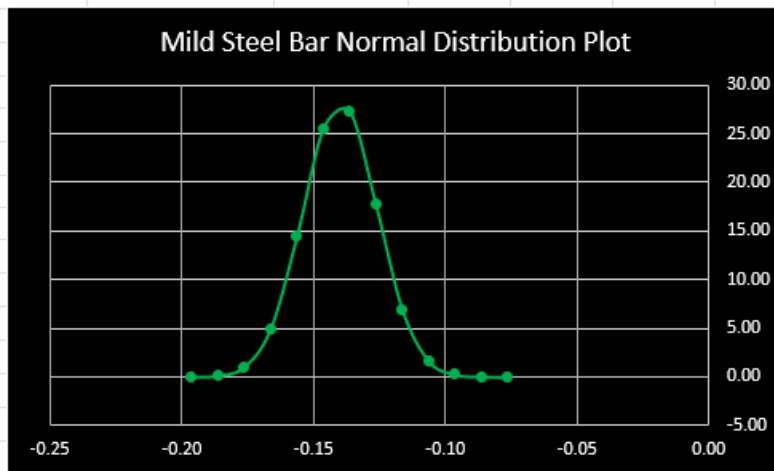


Figure 13 - Mild steel bar normal distribution plot.

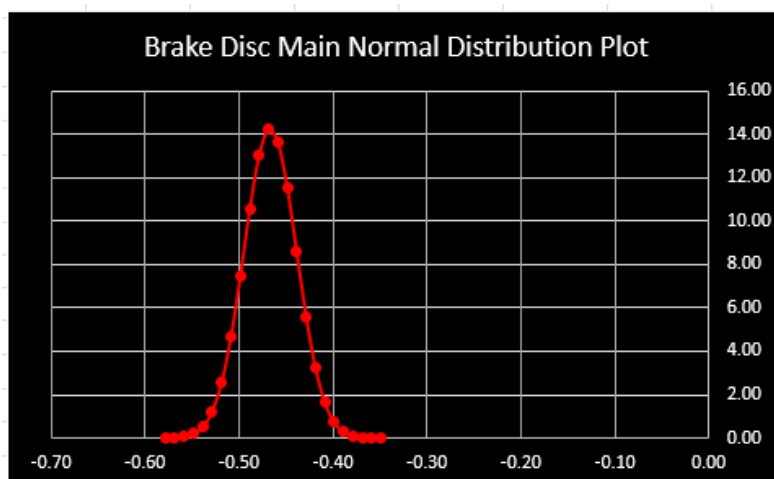


Figure 14 - Brake disc main face normal distribution plot.

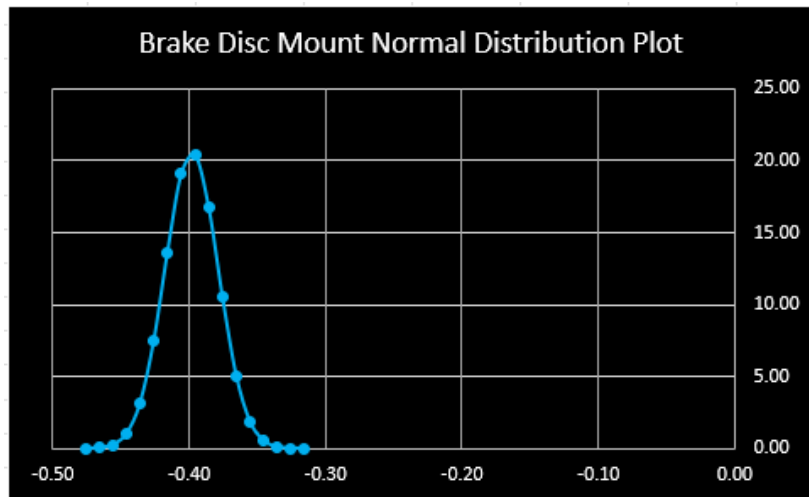


Figure 15 - Brake disc mounting face normal distribution plot.

It is relevant to mention that when carrying out the experiment on both material samples, it is possible that there could have been some errors that occurred. Firstly, the positions that were tested on the mild steel bar were estimated to be at around 0, 20, 40, 60, and 80mm locations along the bar, as specified in figure 8. This was executed to the best of operator ability however there was no true way to ensure that the end of the test probe was exactly at the desired location. This therefore suggesting that this could have been a source of error.

When testing each of the material samples and using a single crystal probe to test for flaws, it was difficult to ensure that the same amount of pressure was being applied through the probe to the test surface at each iteration. It was noted that if there was more pressure applied through the probe, then the result being displayed was significantly affected and therefore would provide a different reading. The amount of pressure applied at each iteration was kept as similar as possible each time by the operator to reduce the impact of this potential source of error.

5.2 Part Two

Calculations carried out for part two of this paper were like the calculations used in part one to plot normal distribution. Using Microsoft Excel, mean values for each of the operators' measurements were calculated. Mean through wall thickness of each defect was also calculated. Standard deviation was also calculated.

Using the NORMDIST function in Excel allowed normal distribution to be calculated which could then be used to create a normal distribution plot.

Through Wall Thickness Analysis													
	Defect	true size	Op1	Op2	Op3	Op4	Op5	Op6	Op7	Op8	Op9	Op10	Mean TWT
1	A	0.25	0.50	0.50	0.00	1.00	0.00	0.50	0.50	0.80	1.00	0.30	0.51
2	B	0.27	0.73	1.20	0.50	1.00	0.00	1.00	0.50	0.80	1.00	1.20	0.79
3	C	0.28	0.76	1.00	1.20	1.00	0.00	0.50	0.50	1.30	1.00	0.70	0.80
4	D	0.40	0.91	0.50	1.00	1.20	1.00	1.00	0.60	1.50	1.00	0.80	0.95
5	E	0.40	0.98	1.20	1.00	1.40	1.00	1.10	0.20	1.60	1.00	0.90	1.04
6	F	0.50	0.79	0.90	1.00	1.10	1.00	0.80	0.00	1.00	1.20	0.50	0.83
7	G	0.52	1.01	1.50	1.10	0.90	1.50	1.00	1.00	0.90	1.00	0.70	1.06
8	H	0.55	0.96	1.20	0.80	0.50	0.90	1.20	1.30	1.60	1.00	0.40	0.99
9	I	0.70	1.35	1.50	0.90	2.00	1.60	1.20	1.60	2.20	1.00	1.00	1.44
10	J	0.98	1.31	1.00	0.80	1.90	2.00	1.60	0.50	1.80	1.00	1.40	1.33
11	K	1.12	1.37	0.50	1.00	1.00	1.80	1.80	1.80	2.00	1.50	1.30	1.41
12	L	1.15	1.56	1.80	1.30	2.20	1.00	1.50	1.80	2.00	1.50	1.20	1.59
13	M	1.10	1.60	2.00	1.40	2.00	1.60	1.50	0.50	2.20	2.00	1.60	1.64
14	N	1.30	1.73	2.10	0.90	2.20	2.00	2.00	1.70	2.00	1.50	1.70	1.78
15	O	1.60	1.56	0.80	0.90	2.00	2.00	1.50	1.20	2.00	2.00	1.50	1.55
16	P	1.80	2.14	2.00	1.40	2.40	2.00	3.20	2.20	2.50	2.50	1.10	2.14
17	Q	2.10	2.49	1.80	3.30	3.50	2.50	3.00	2.00	3.20	2.00	2.60	2.54
18	R	2.70	2.97	3.00	3.20	2.80	2.50	3.50	2.50	3.50	3.50	2.20	2.97
19	S	4.90	4.87	4.50	4.50	5.70	4.50	4.40	4.20	5.40	5.50	5.50	4.91
20	T	6.00	6.17	5.50	6.20	7.00	6.50	5.50	5.30	6.70	6.50	6.00	6.14
21	U	7.50	6.99	6.00	6.25	8.00	7.20	6.50	6.50	6.90	8.00	6.50	6.88
	AVG												2.06
	MIN												0.30
	MAX												3.82
	Mean Op		2.03	1.93	1.79	2.42	2.03	2.11	1.73	2.47	2.22	1.88	

Figure 16 - Through wall thickness Excel data

Using data shown in figure 16, the following plots were created.

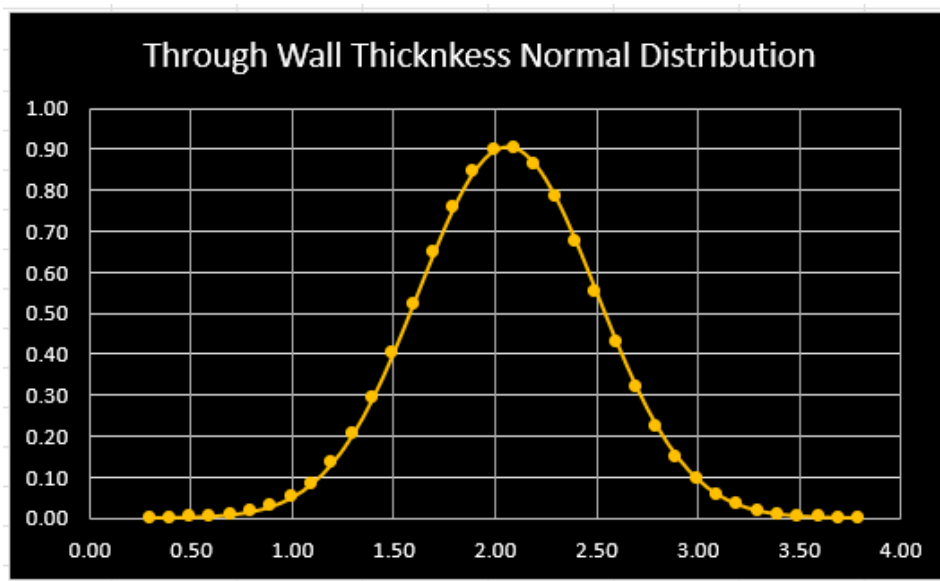


Figure 17 - Through wall thickness normal distribution plot.

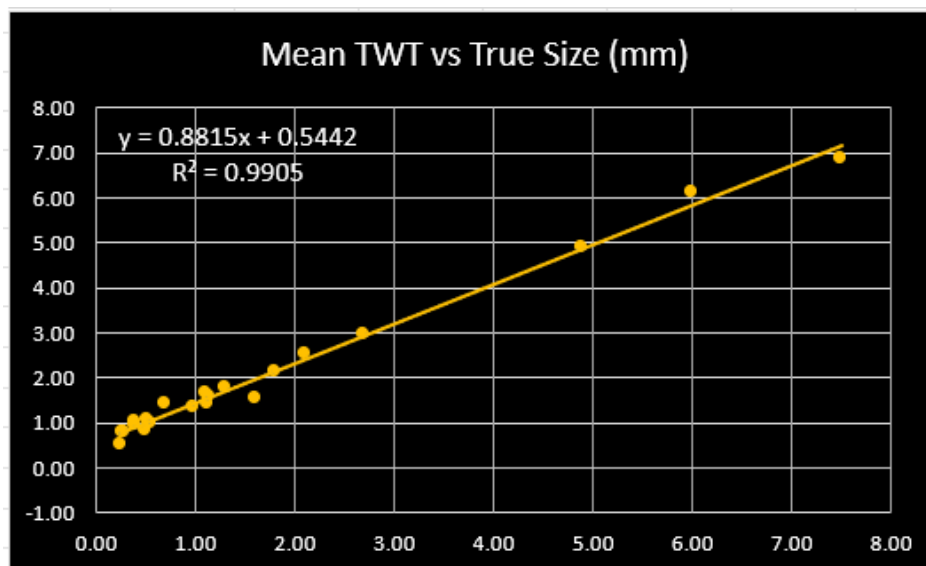


Figure 18 - Through wall thickness scatter plot.

6 Results and Discussion

6.1 Part One

Results gathered from the experiment conducted for part one of this paper are shown in figures 8 and 9. The results were deemed to be reasonable. There was little variance between results at each position. The standard deviation of the mild steel block results varied between 0.01 and 0.02 for each position which suggests that the results gathered were comprehensive. If there was large variance of the results from one position to another, then this would suggest that there was a source of error within the procedure.

6.2 Part Two

Following analysis of the through wall thickness data, various plots were created. Some of these plots have been shown earlier in this report. To assess the error of each operator, a simple calculation of subtracting operator measurement from the true size for each of the 21 defects was conducted. Those values compared each operator measurement to the true size of the defect which was a suitable method of assessing the accuracy of each operator and their measurements. These values were gathered, and a mean was calculated which was then used to create the following plot in Microsoft Excel. This process was repeated for each defect also.

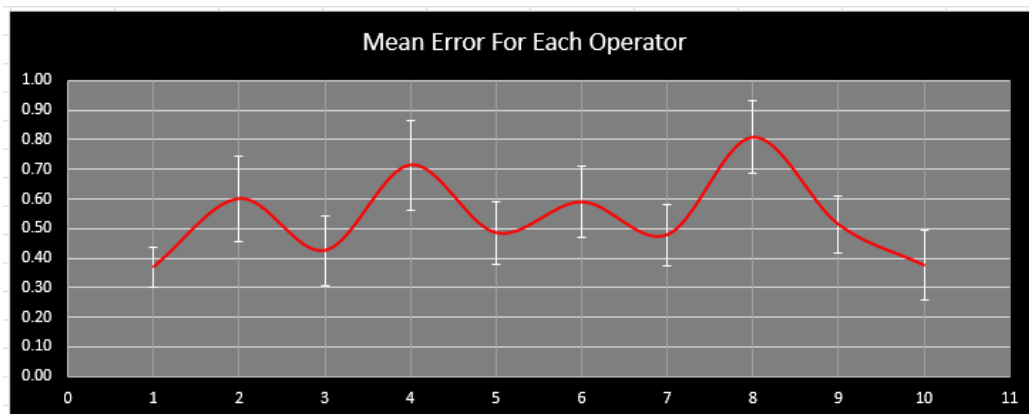


Figure 19 - Mean error for each of the 10 operators.

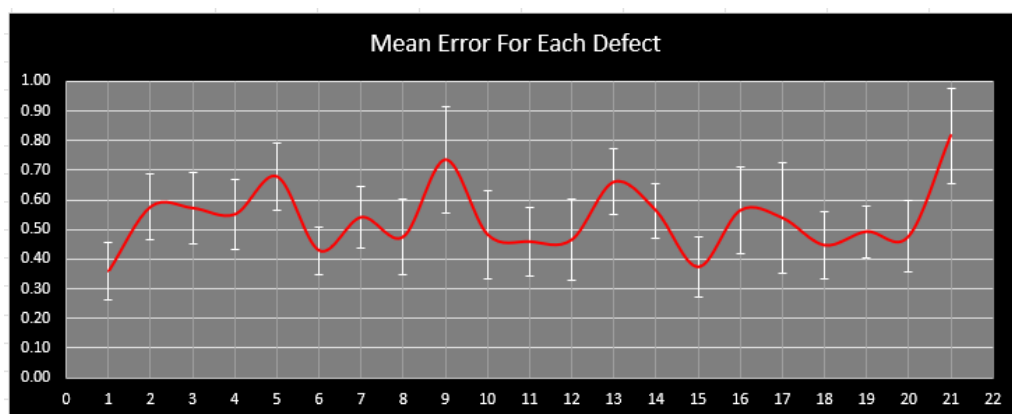


Figure 20 - Mean error for each of the 21 defects.

Error bars were used to further highlight the accuracy of the data that has been plotted. Longer error bars indicate that the data is not totally reliable and that there is a wider spread in the data. Shorter error bars indicate that the data is much more concise, and the data can be seen to be more reliable [6].

Figure 19 shows that operators 2, 4, and 8 have long error bars which suggests that measurements taken by those operators were less accurate than measurements taken by the 7 other operators. Figure 20 shows that defect numbers 9 and 21 have higher mean error compared with other defect measurements in the plot. Other than the defects highlighted previous, all other defects have a relative mean error that follows a flat trend, this can be observed on figure 20.

7 Conclusion

Based on findings discussed within this report, it can be concluded that for part one of the paper, results gathered from the experiment and attenuation coefficient values for each material sample can be seen as suitable. There are some elements of the experiment that could be improved, as mentioned previous, like ensuring the accuracy of the probe location on the material sample. Another method of potentially improving the experiment accuracy and validity would be to develop a method of ensuring that pressure being applied through the probe is consistent each time, thus ensuring a consistency of recorded results throughout the experiment. However even with those points considered, the experiment was deemed a success and provided valuable data that could be used successfully to calculate the material attenuation coefficient using the method outlined within this report.

To conclude part two of the paper, it is deemed that the experimental process and operators used to gain through wall thickness measurements are generally good, however as outlined previous, there were some operators that seemed to record measurements that had higher mean error when compared with the other operators, suggesting that there was some source of error within their method of obtaining the measurements.

8 Bibliography

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