A UK Residual Stress Intercomparison Exercise - An Examination of the XRD and Hole Drilling Techniques

by

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SUMMARY

As part of the CPM4.5 project on the *Measurement of Residual Stress in Components,* an intercomparison exercise has been carried out to determine the accuracy and uncertainties associated with the X-ray diffraction and hole drilling techniques.

The intercomparison was carried out in two iterations. In the first stage the participants were asked to perform the measurements according to their own in-house procedures. In the second iteration, a more detailed and specific test procedure was prescribed to try and reduce the scatter in the data and improve confidence in the measurement technique.

Materials examined include a shot peened spring steel, a quenched 7010 Al block, a heavily textured 6082 Al alloy and an aluminium friction stir weld. Sixteen organisations participated in the exercise.

Results showed that generally there was less scatter in the XRD data. Problems were evident with some of the hole drilling results, particularly for the shot peened steel specimen where the stress profile in the specimen was non-uniform. In both cases significant improvements in the accuracy and quality of the measurements were achieved in the second iteration.

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ISSN 1473-2734

National Physical Laboratory, Teddington
Middlesex, TW11 0LW, UK

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CONTENTS

1 Introduction **1**
2 Materials Examined **1**
2.1 Materials used in the first iteration 1
2.2 Materials used in the second iteration 2
3 Participating Laboratories **3**
4 X-ray Diffraction Results **4**
4.1 First Iteration 4
4.1.1 Equipment Details 4
4.1.2 Results from the first iteration 6
4.2 Second Iteration 12
4.2.1 Equipment Details 12
4.2.2 Results from the second iteration 14
4.3 Comparison of first and second iteration XRD results 17
5 Hole Drilling Results **18**
5.1 Equipment Details 18
5.2 First iteration 19
5.2.1 Strain data 19
5.2.2 Stress data 30
5.2.3 Further Analysis of the results 33
5.3 Second Iteration 36
5.3.1 Equipment Details 36
5.3.2 Strain data 36
5.3.3 Stress data 43
5.3.4 Measurements at fine depth increments 45
5.3.5 Comparison of first and second iteration HD results 46
6 Comparison of the XRD and hole drilling data **47**
7 Summary and Conclusions **48**
References **49**
Acknowledgements **49**

INTRODUCTION

As part of the CPM4.5 project on the *Measurement of Residual Stress in Components,* an intercomparison exercise has been carried out to determine the accuracy and uncertainties associated with the X-ray diffraction (subsequently referred to simply as XRD) and hole drilling techniques.

The intercomparison was carried out in two iterations. In the first stage the participants were asked to perform the measurements according to their own in-house procedures. In the second iteration, a more detailed and specific test procedure was prescribed to try and reduce the scatter in the data and improve confidence in the measurement technique.

Materials examined include a shot peened spring steel, a quenched 7010 Al block, a heavily textured 6082 Al alloy and an aluminium friction stir weld. Sixteen organisations participated in the exercise.

Further details of the materials examined and the organisations taking part are included in the subsequent sections. The XRD results from both iterations are then considered in Section 4, with the corresponding hole drilling data presented in Section 5. A short comparison of the respective measurements is included in Section 6, together with the summary and conclusions from the exercise in Section 7.

2 MATERIALS EXAMINED

2.1 Materials used in the first iteration

Two materials were examined in the first iteration – a CCr3 spring steel and a quenched 7010 aluminium alloy. Both materials were examined by the XRD and hole drilling groups.

The steel specimens were in the form of blocks approximately 90 x 90 x 25mm, supplied by Corus. Half of each steel specimen was shot peened by the Metal Improvement Company using Process 19847 with 4.5mm balls to introduce a compressive stress profile into the surface layers, the remaining half was left in the as-received (nominally stress-free) condition. The 7010 aluminium specimens were of similar dimensions and were supplied by Airbus UK and solution treated and cold water quenched at NPL. Thus two different materials and three stress states were examined in the first iteration.

Each participant was asked to measure the residual stress at three pre-defined locations on the shot-peened and as-received sides of the steel, and at two locations on opposite faces of the aluminium block, as shown in Figure 1. No other conditions were imposed on the test procedure. In the first iteration, laboratories were free to carry out the test as per their usual procedure, provided all parameters were recorded.

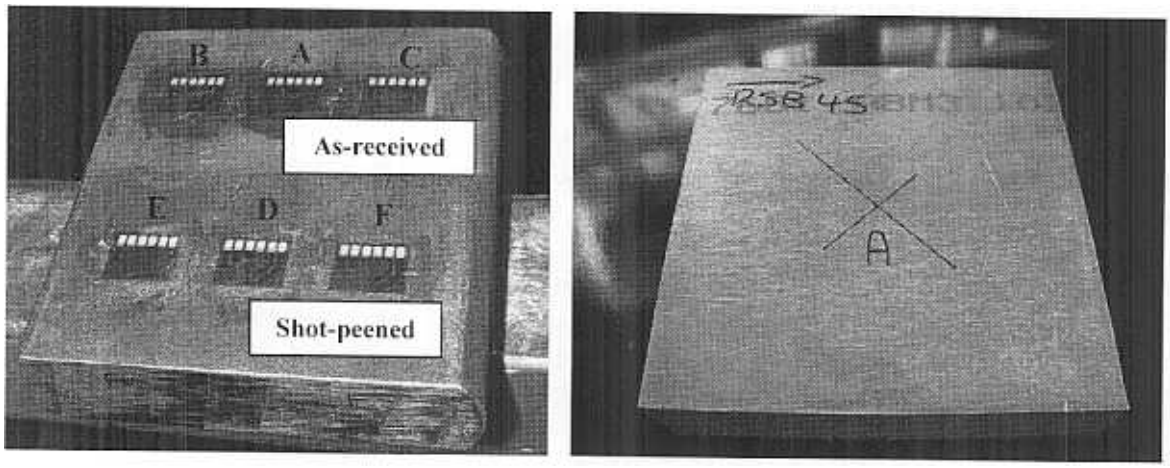


Figure 1a: Spring steel sample (left), half as-received, half shot-peened; 7070 aluminium sample (right), test location B on rear surface

2.2 Materials used in the second iteration

For both the XRD and hole drilling groups, repeat measurements were made on the shot peened spring steel. For the hole drilling measurements, the surface preparation of each block was carried out at NPL to a standard procedure prior to distribution to eliminate the effect of surface preparation on subsequent results. In addition, the hole drilling group examined an aluminium friction stir weld, supplied by Airbus UK, and the XRD group a heavily textured 6082 aluminium alloy, provided by QinetiQ.

For the XRD tests in the second iteration the same block of material was passed amongst the participating laboratories, so that material variability was not a factor in the measurements and the scatter and uncertainty in the results are due only to the individual laboratory's measurement procedure.

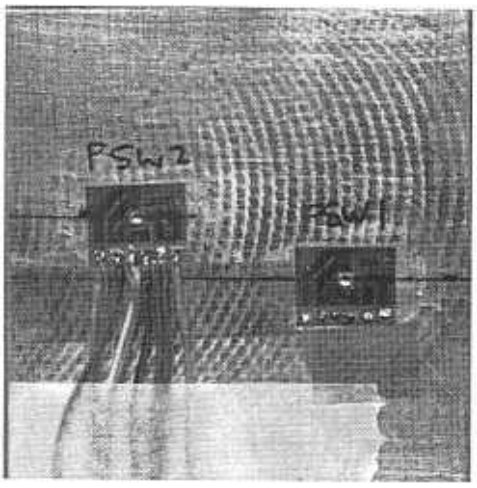


Figure 1b: Friction stir weld specimen used in the second iteration hole drilling exercise

3 PARTICIPATING LABORATORIES

Table 1 below shows the list of organisations taking part in the intercomparison exercise. Not all participants carried out measurements on all the materials, nor did every organisation take part in the second iteration. Only NPL and Corus performed both XRD and hole drilling measurements.

Organisation	Country	Hole Drilling	XRD
Bristol University	UK	✓	
Corus	UK	✓	✓
IPEN/CEN-SP	Brazil		✓
Manchester Materials Science Centre	UK		✓
Measurements Group	UK	✓	
NPL	UK	✓	✓
Open University	UK		✓
Rolls Royce plc	UK		✓
Rolls Royce Marine	UK	✓	
Stresscraft	UK	✓	
Stress Engineering Technologies	UK	✓	
Stresstech	Finland		✓
QinetiQ	UK		✓
University of Newcastle Design Unit	UK		✓
University of Oxford	UK		✓
University of Limerick	Ireland		✓

Table 1: List of organisations taking part in the exercise

To retain anonymity the participants were identified by code. For the hole drilling exercise the laboratories involved were identified by numbers 1-8, for XRD the organisations were coded A-L.

4 X-RAY DIFFRACTION RESULTS

4.1 First Iteration

Twelve organisations participated in the first iteration of the XRD exercise, four of these were from industry with the remaining coming from academia. Each participant was asked to perform measurements on the shot-peened spring steel sample and the heat-treated 7010 aluminium sample. Details of the equipment used are given below.

4.1.1 Equipment Details

Six different X-ray machines were used in the exercise - a mix of both portable equipment and lab based diffractometers (4 portable and 5 lab based). Around half of the participants used position sensitive detectors (PSD), which makes the measurement quicker. Interestingly it was the older lab based equipment that generally did not use PSD's. No equipment details were supplied for Lab J.

Lab ID	Machine	Detector	Geometry	Irradiated Area	X-ray source
A	XSTRESS 3000	PSD	Psi	Variable	CrKα
B	Bruker D500	SC	Psi	Variable	CrKα
C	TEC1610-2b	PSD	Psi	Variable	CrKα
D	XSTRESS 3000	PSD	Psi	Variable	CrKα
E	Bruker D500	SC	Psi	Variable	CrKα
F	Rigaku Strain Flex PSF-2M	SC	Psi	Variable	CrKα
G	Bruker D5005	PSD	Psi	Constant	CrKα
H	XSTRESS 3000	PSD	Psi	Constant	CrKα
I	Rigaku D-Max 2000	SC	Psi	Variable	CrKα
J	?	?	?	?	?
K	Bruker D8	GADDS	Omega	Variable	CrKα
L	Philips X-Pert MPD	SC	Omega	Constant	CuKα

Key : PSD Position Sensitive Detector, SC Scintillation Counter

Table 2: Details of XRD equipment used in the first iteration

In the first iteration, the laboratories were asked to follow their usual in-house procedures, and all chose to use a CrKα anode, which is generally considered to be the most appropriate to use.

Details of the measurement set-up, data correction and peak fitting routines for the spring steel and aluminium specimens are given in Tables 3 and 4 respectively.

Lab ID	2θ range (°)	2θ step size (°)	Count time per step (s)	Background subtraction	$K\alpha_2$ stripping	LPA correction	Peak Fitting Routine	Stress Evaluation	Number of Psi tilts
A	?	?	?	?	?	?	?	?	9
B	13	0.05	2	Yes	Yes	Yes	Psuedo-Voigt Fit	Linear & Elliptical	13
C	14	0.055	0.4	Yes	Yes	No	Parabolic	Biaxial	9
D	37	0.029	5	Yes	Yes	No	Cross Correlation	Linear	9
E	9.8	0.02	1.5	Yes	Yes	Yes	Ave Sliding Gravity	Elliptical	9
F	30	0.35	6.5	?	?	?	?	?	4
G	6	0.01	0.25	Yes	Yes	Yes	Sliding Gravity	Linear	6
H	?	0.02	7	Yes	No	No	Cross Correlation	Linear	4
I	3.6	0.05	50	Yes	Yes	LP only	Peak top (parabolic)	Linear	7

Table 3: Details of measurement set-up, data correction and peak fitting routines – for the spring specimen– 1st iteration

Lab ID	2θ range (°)	2θ step size (°)	Count time per step (s)	Background subtraction	$K\alpha_2$ stripping	LPA correction	Peak Fitting Routine	Stress Evaluation	Number of Psi tilts
A	?	0.02	1	Yes	No	No	Cross Correlation	Linear	12
B	4.5	0.02	5	Yes	Yes	Yes	Psuedo-Voigt Fit	Linear	13
C	?	?	?	?	?	?	?	?	?
D	37	0.029	15	Yes	Yes	No	Cross Correlation	Linear	9
E	7	0.02	2	Yes	Yes	Yes	Ave Sliding Gravity	Linear	9
F	8.6	0.17	10	?	?	?	?	?	?
G	5	0.005	500	Yes	Yes	Yes	Sliding Gravity	Elliptical	12
H	?	0.02	60	Yes	No	No	Cross Correlation	Linear	4
K	11.1	0.04	200	Yes	Yes	Yes	Sliding Gravity	Elliptical	10
L	3.5	0.03	5	Yes	Yes	Yes	Centre of Gravity	Linear	8

Table 4: Details of measurement set-up, data correction and peak fitting routines – for the Quenched Al specimen– 1st iteration

Although the measurement range and step size is governed to a large extent by the type of detector used, for the spring steel specimens there is a wide variation over the measurement range, spanning from 3.6° 2θ to 30° 2θ.

No specifications were given to the participants as to how to treat the data once it had been collected. Tables 3 and 4 show the data processing methods used for the two materials. All of the participants that provided details used background subtraction and the majority removed the $K\alpha_2$ peak from the data, but only around half performed some form of Lorentz Polarization and Adsorption correction. There was no one favoured peak fitting method. Most participants used 9 psi tilts, evenly split between positive and negative psi values. This is mirrored in the count time used to collect the data, with counts ranging from 0.4 s/° step to 50 s/° step. Generally speaking laboratories with PSD's used the short count times, reflecting the speed of data collection with this type of detector.

For the quenched aluminium specimens, similar conditions were used but there were significantly longer count times in most cases. Similar numbers of psi tilts were also used.

4.1.2 Results from the first iteration

Results from the first iteration XRD results are given in Tables 5 and 6 for the spring steel (as received and shot peened) and in Table 7 for the quenched aluminium samples. Results are presented in terms of the quoted stress values and the associated error. For at least one position on each specimen, the "reference" values measured at NPL before the specimens were distributed is also given for comparison. The results are plotted in Figs 5-9.

It should be noted that the errors quoted with the results are those returned from the software and are not based on the uncertainty calculations associated with the measurement method itself.

Lab ID	Pos A			Pos B		Pos C		All 3 positions	
	Stress (MPa)	± Error (MPa)	NPL (MPa)	Stress (MPa)	± Error (MPa)	Stress (MPa)	± Error (MPa)	Mean (MPa)	± SD (MPa)
A	33	19	-10	3	12	20	18	**19**	**15**
B	-12	4	-1	-42	2	-9	8	**-21**	**18**
C	-10	17	1	3	8	-36	6	**-14**	**20**
D	-8	9	8	0	9	78	12	**23**	**48**
E	-23	2	-23	24	3	-3	3	**-1**	**24**
F	-29	11	-10	24	9	-59	6	**-21**	**42**
G*	2 54*	23 11	1	43 76*	12 10	32 71*	24 6	**67**	**12**
H	-2	13	-9	2	4	31	12	**10**	**18**
I			1	-13	3	-53	3	**-33**	**28**
Mean	0 *	11	-5	9 *	7	4 *	8	**Pop mean =**	
S.Dev	29*	6	9	32 *	4	50 *	5	**5 ± 37**	

* Mean and standard deviation using corrected values from Lab G

Table 5: XRD results on the spring steel in the AS RECEIVED condition (1st iteration)

Lab ID	Pos D			Pos E		Pos F		All 3 positions	
	Stress (MPa)	± Error (MPa)	NPL (MPa)	Stress (MPa)	± Error (MPa)	Stress (MPa)	± Error (MPa)	Mean (MPa)	± SD (MPa)
A	-523	17	-496	-548	15	-535	18	**-535**	**13**
B	-572	28	-555	-607	31	-593	28	**-591**	**18**
C	-525	31	-588	-528	22	-523	32	**-525**	**3**
D	-519	29	-595	-540	13	-514	22	**-524**	**14**
E	-561	27	-561	-544	29	-569	28	**-558**	**13**
F	-525	13	-566	-514	12	-511	14	**-517**	**7**
G*	-356 -534*	41 59	-573	-316 -483*	16 22	-332 -535*	24 29	**-517**	**30**
H	-531	17	-579	-482	25	-514	12	**-509**	**25**
I			-557	-337 *	23	-396 *	28	**-367 ***	**42**
Mean	-538 *	29	-574	-528 *	22	-537 *	24	**Pop mean =**	
S.Dev	20*	15	16	43 *	7	32*	8	**-535 * ± 30**	

* Mean and standard deviation using corrected values from Lab G, & excluding Lab I

Table 6: XRD results on the spring steel in the SHOT PEENED condition (1st iteration)

For the spring steel, the results for Lab G were repeated because of problems with their PSD calibration. Both sets of data (uncorrected and repeated) are included for comparison in Figs 5 and 6, and Figs 7 and 8 and in the tables. Only the corrected values have been used in calculating the mean and standard deviations.

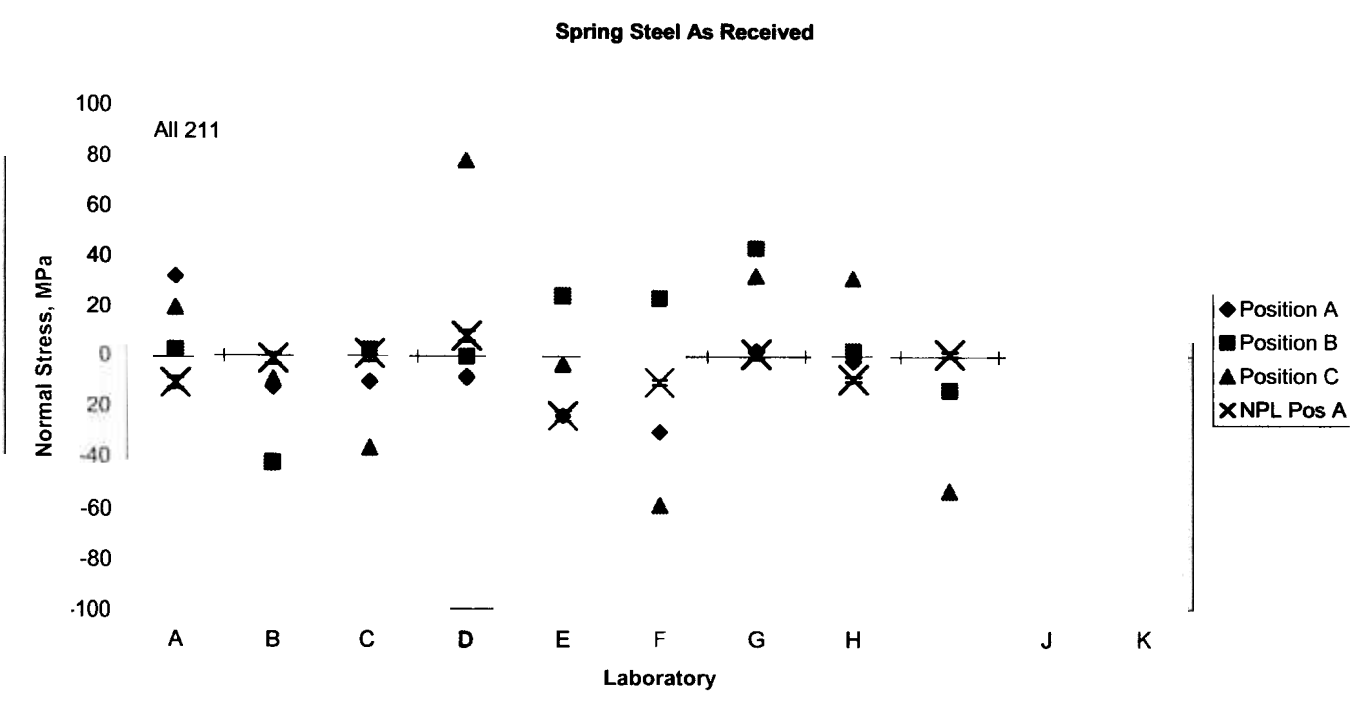


Fig 5: XRD results on the spring steel in the AS RECEIVED condition (1st iteration)

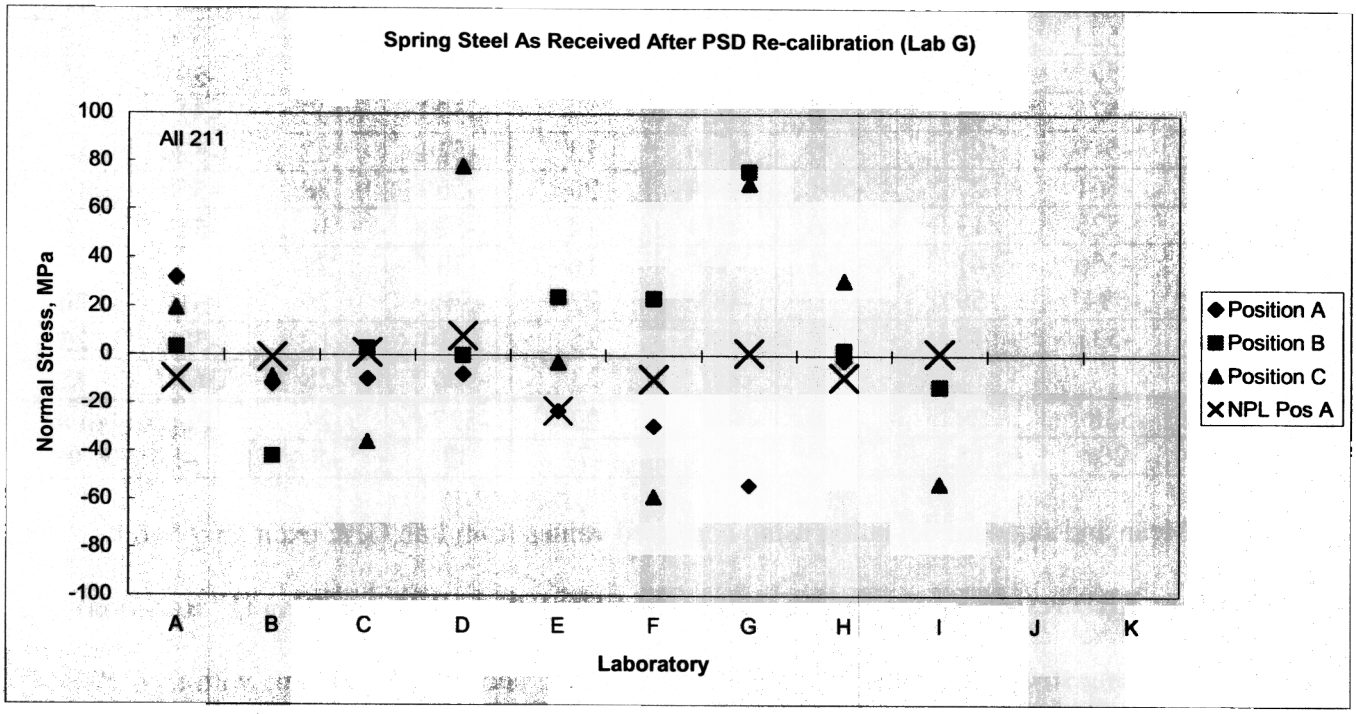


Fig 6: XRD results on the spring steel in the AS RECEIVED condition (1st iteration) - CORRECTED Lab G

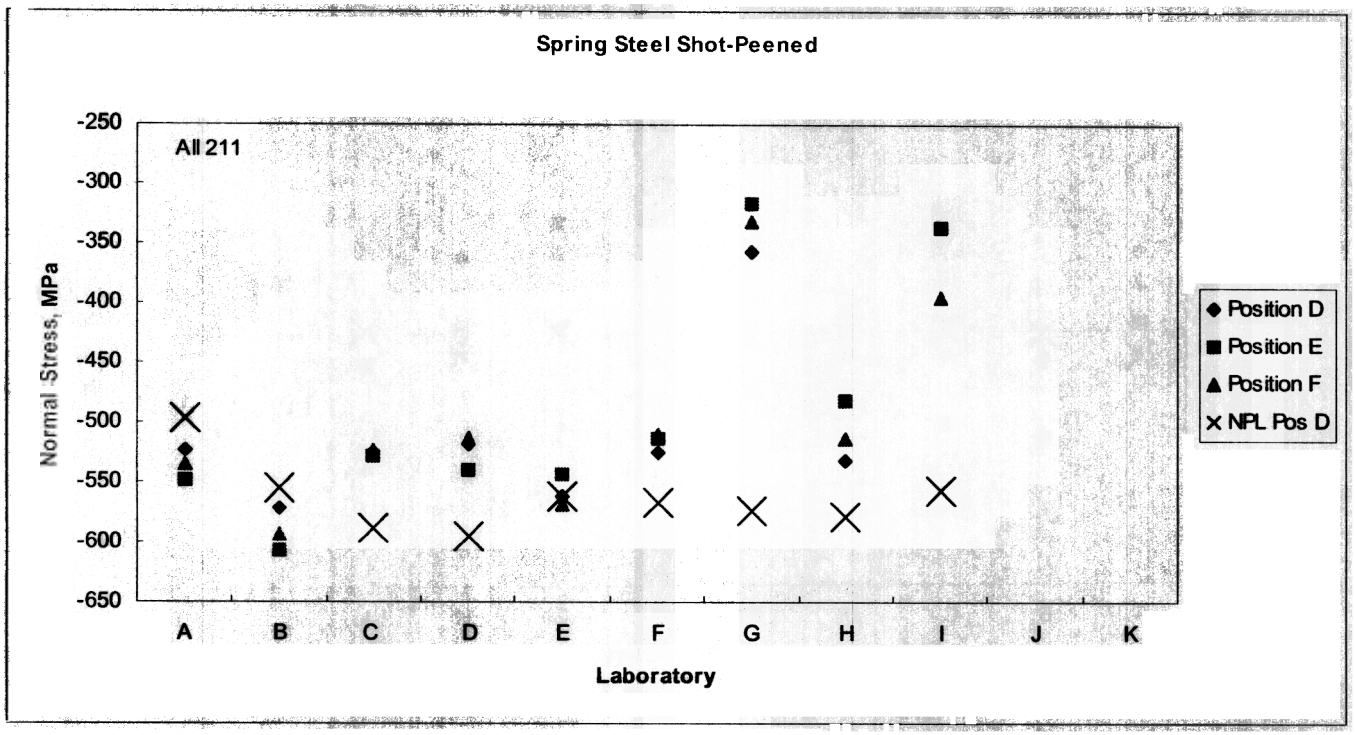


Fig 7: XRD results on the spring steel in the SHOT PEENED condition (1st iteration)

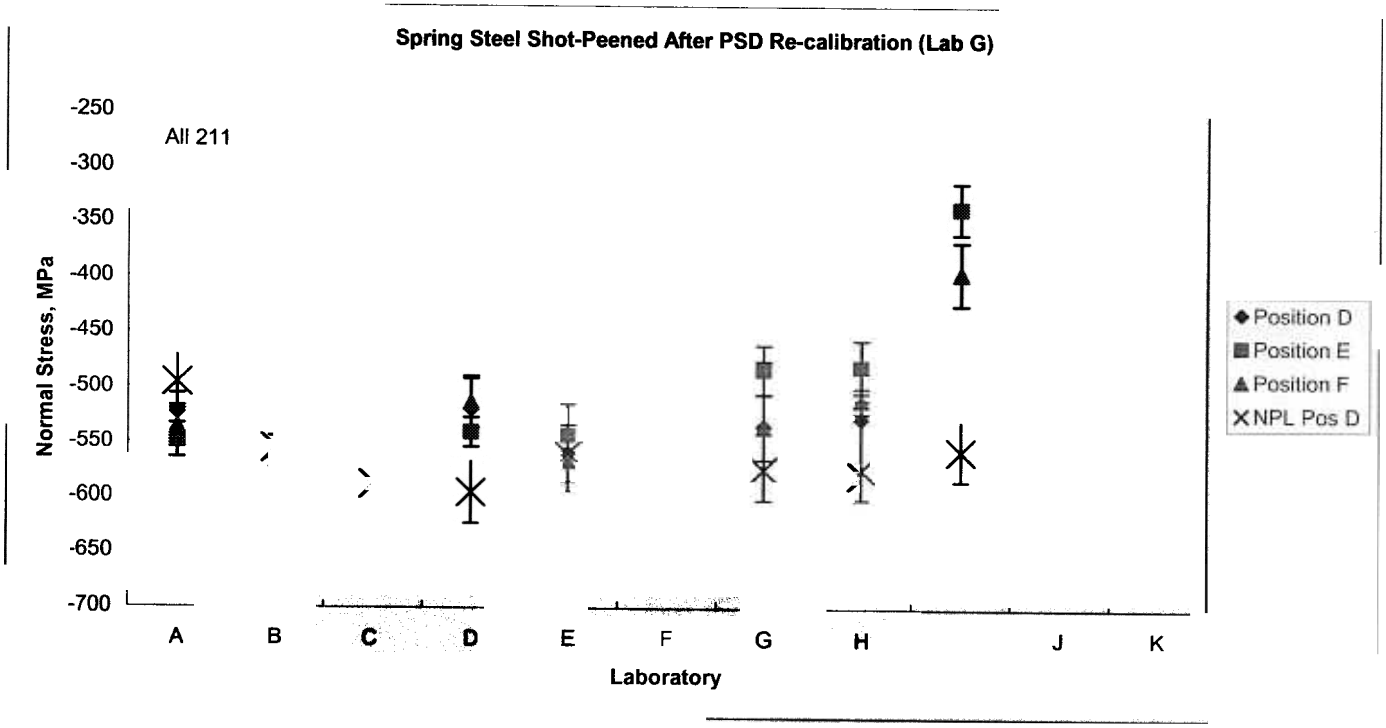


Fig 8: XRD results on the spring steel in the SHOT PEENED condition (1st iteration) - CORRECTED Lab G

Lab ID	Pos A			Pos B			Mean of A & B	
	Stress (MPa)	± Error (MPa)	NPL (MPa)	Stress (MPa)	± Error (MPa)	NPL (MPa)	Mean (MPa)	± SD (MPa)
A	-203	17	-210	-171	20	-196	**-187**	**23**
B	-203	5	-208	-201	8	-205	**-202**	**1**
C	-179	31	-191	-193	28	-191	**-186**	**10**
D	-189	35	-217	-218	22	-212	**-204**	**21**
E	-173	9	-179	-184	8	-191	**-179**	**8**
F	-169	9	-192	-174	22	-192	**-172**	**4**
G	-174	8	-198	-185	9	-199	**-180**	**8**
H	-193	20	-181	-148	0	-179	**-171**	**32**
J	-146	23	-202	-173	19	-184	**-160**	**19**
K	-145	6	-181	-157	9	-177	**-151**	**8**
Mean	**-177**	**16**	**-196**	**-180**	**15**	**-193**	**Pop Mean = -179 ± 20**	
S. Dev.	**21**	**11**	**13**	**21**	**9**	**11**		

Table 7: XRD results on the Quenched Aluminium specimen (1st iteration)

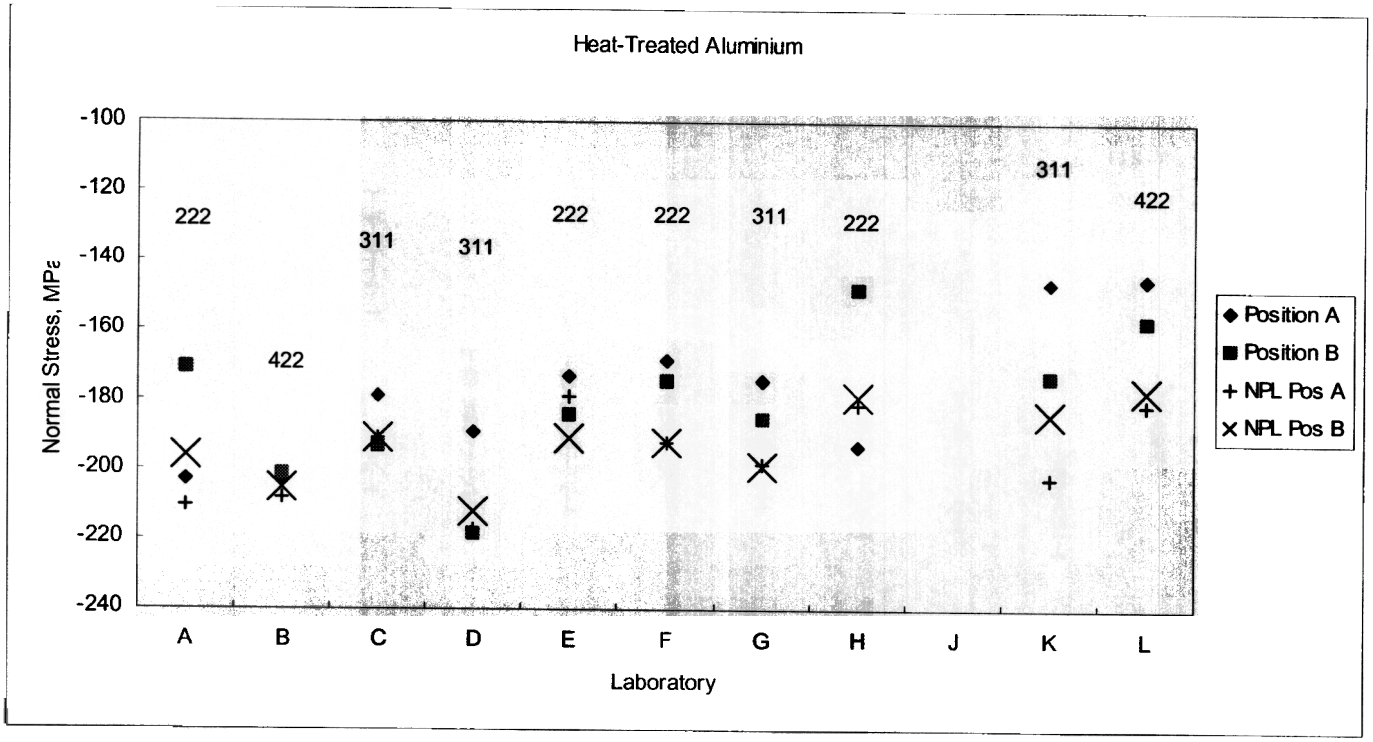


Fig 9: XRD results on the Quenched Aluminium specimen (1st iteration)

Table 8 summarises all the results from the XRD first iteration according to Lab and material type. Results are colour coded to indicate which Laboratory's results are higher or lower than the mean and the NPL "reference" values.

Lab ID	As received spring steel			Shot peened spring steel			Quenched 7010 Aluminium		
	Mean of all Positions ABC	Deviation from pop mean	Deviation from NPL "ref" at Pos A	Mean of all Positions DEF	Deviation from pop mean	Deviation from NPL "ref" at pos D	Mean of all Positions AB	Deviation from pop. mean	Deviation from NPL "ref"
A	19	14	43	-535	0	-27	-187	-8	16
B	-21	-26	-11	-591	- 56	-17	-202	-23	5
C	-14	-19	-11	-525	12	63	-186	-7	5
D	23	18	-16	-524	11	76	-204	-25	11
E	-1	6	0	-558	-20	0	-179	0	6
F	-21	26	-19	-517	18	41	-172	7	21
G	67	62	53	-517	18	39	-180	-1	19
H	10	5	7	-509	26	48	-171	8	10
I	-33	-38	-1	-367	-168				
J							-160	19	34
K							-151	28	28

Key: higher; lower

Population mean for the as-received steel = 5 ± 37 MPa
Population mean for the shot peened steel = -535 ± 30 MPa (excl Lab I)
Population mean for the quenched Al = -179 ± 20 MPa

Table 8: Statistics for 1st XRD iteration (All stress values in MPa)

4.2 Second Iteration

In the second iteration of the XRD exercise, repeat measurements were carried out on the quenched aluminium block from the first iteration, together with new measurements on a heavily textured 6082 aluminium alloy. In this case the same sample of material was tested by each of the Labs, thus eliminating the material variability from the measurements. Only one measurement location was examined for each material, but participants were asked to make a number of repeat measurements at that location to get some indication of their repeatability. Eight laboratories participated in the second iteration and details of the equipment are given in Table 9 below. It should be noted that the Lab IDs used are not necessarily the same as the first iteration – the results were coded according to the order in which they were received. A summary of the performance of the individual laboratories for each iteration is given in Section 4.3.

4.2.1 Equipment Details

Lab ID	Machine	Detector	Geometry	Irradiated Area	X-ray source
A	XSTRESS 3000	PSD	Psi	Variable, 5mm dia	CrKα
B	?	?	?	?	?
C	Bruker D500	SC	Psi	Variable	CrKα
D	TEC1610-2b	PSD	Psi	Variable, 3mm dia	CrKα
E	Bruker D500	SC	Psi	Variable	CrKα
F	XSTRESS 3000	PSD	Modified Psi	3mm dia	CrKα
G	XSTRESS 3000	PSD	Psi	2mm dia	CrKα
H	Proto	PSD	Omega	2mm round	CrKα

Key : PSD Position Sensitive Detector, SC Scintillation Counter

Table 9: Details of XRD equipment used in the second iteration

Four different X-ray machines were used in the second iteration, consisting of both portable equipment and lab based diffractometers (4 portable and 3 lab based as reported). Three of the four reported portable machines were the same, the XSTRESS 3000. The majority of the participants again used position sensitive detectors, which makes the measurement quicker. Given that four of the participants were using similar equipment, the lack of variation is not surprising. For this iteration, the laboratories were asked to follow a more standardised procedure - all were asked to measure with a CrKα anode, but the range of the measurement and data collection and analysis was left to the laboratory to decide.

Tables 10 and 11 show the details of the measurement parameters and data processing methods used. A wide variation over the measurement range is still apparent, spanning from 5.5° 2θ to 37° 2θ. This range is very similar to the first iteration. The range of count times used to collect the data is less than previously, with counts ranging from 3 s/° step to 100 s/° step. Generally speaking laboratories with PSD's used the short count times, reflecting the speed of data collection with this type of detector.

No specifications were given as to how to treat the data once it had been obtained. Generally all the participants corrected for background, $K\alpha_2$ and LPA. There was no one favoured peak fitting method, and since there were no apparent shear stresses the majority used a linear fit to

Lab ID	2θ range (°)	2θ step size (°)	Count time per step (s)	Background subtraction	$K\alpha_2$ stripping	LPA correction	Peak Fitting Routine	Stress Evaluation	Number of Psi tilts
A	37	0.029	15	Yes	Yes	No	Cross Correlation	Linear	7
B	?	?	20	?	?	?	?	?	16
C	10	0.02	3	Yes	Yes	Yes	Average Sliding Gravity	Elliptical	9
D	15.3	0.06	100	Yes	Yes	No	Parabolic fit to top 20%	Linear	9
E	5.5	0.05	4	Yes	Yes	Yes	Pseudo Voigt Fit	Linear	13
F	13	0.03	20	Yes	Yes	No	Pearson VII	Linear	2
G	?	?	7	Yes	Yes	Yes	Cross Correlation	Linear	6
H	?	0.03	100	Yes	No	Yes	Gaussian	Linear	22

Table 10: Details of measurement set-up, data correction and peak fitting routines – for the repeat tests on the Quenched Al specimen– 2nd iteration

Lab ID	2θ range (°)	2θ step size (°)	Count time per step (s)	Background subtraction	$K\alpha_2$ stripping	LPA correction	Peak Fitting Routine	Stress Evaluation	Number of Psi tilts
A	37	0.029	15	Yes	Yes	No	Cross Correlation	Linear	9
B	?	?	1500	?	?	?	?	?	16
C	6.9	0.03	18	Yes	Yes	Yes	Average Sliding Gravity	Elliptical	9
D	15.3	0.06	100	Yes	Yes	No	Parabolic fit to top 20%	Linear	15
E	5.5	0.05	6	Yes	Yes	Yes	Pseudo Voigt Fit	Linear	2
F	?	0.03	25	Yes	Yes	No	Pearson VII	Linear	2
G	?	?	5	Yes	Yes	Yes	Cross Correlation	Linear	8
H	17	0.02	20	Yes	No	Yes	Gaussian	Linear	22

Table 11: Details of measurement set-up, data correction and peak fitting routines – for the heavily textured Al – 2nd iteration

the $\sin^2\psi$ graph. There was however some variation in the number of psi tilts used, ranging from 2 to 22. Interestingly the results obtained with 22 psi tilts falls outside the general trend.

4.2.2 Results from the second iteration

In the second iteration of the XRD study the same sample of material was tested by each of the Labs, thus eliminating the material variability from the measurements. Laboratories were asked to carry out a number of repeat measurements at the same location, clearly marked on the specimen. The table below shows the results from the repeat measurements on the quenched aluminium specimens. Most labs carried out 10 repeat tests.

LAB	Stress Measurement, MPa											
	1	2	3	4	5	6	7	8	9	10	Mean	SD
A	-169	-170	-175	-169	-168	-170	-170	-171	-170	-171	-170	2
B	-185	-197	-188	-196	-191	-200	-186	-186	-198	-198	-192	6
C	-206	-204	-203	-203	-203	-204	-205	-204	-205	-206	-204	1
D	-194	-191	-210	-196	-198	-190	-198	-197			-197	6
E	-196	-197	-197	-195	-196						-196	1
F	-190	-191	-191	-189	-190	-190	-191	-190	-190	-190	-190	1
G	-179	-175	-175	-174	-179	-178	-172	-175	-175	-176	-176	2
H	-258	-259	-256	-257	-256	-256	-255	-255	-256	-258	-257	1
											Population Mean = -198 ± 26 MPa	
											Mean of 1st set of measurements (excl Lab H) = -188 ± 12 MPa	
											Mean (excl Lab H) = -189 ± 12 MPa	

Table 12: XRD results on the Quenched aluminium (2nd iteration)

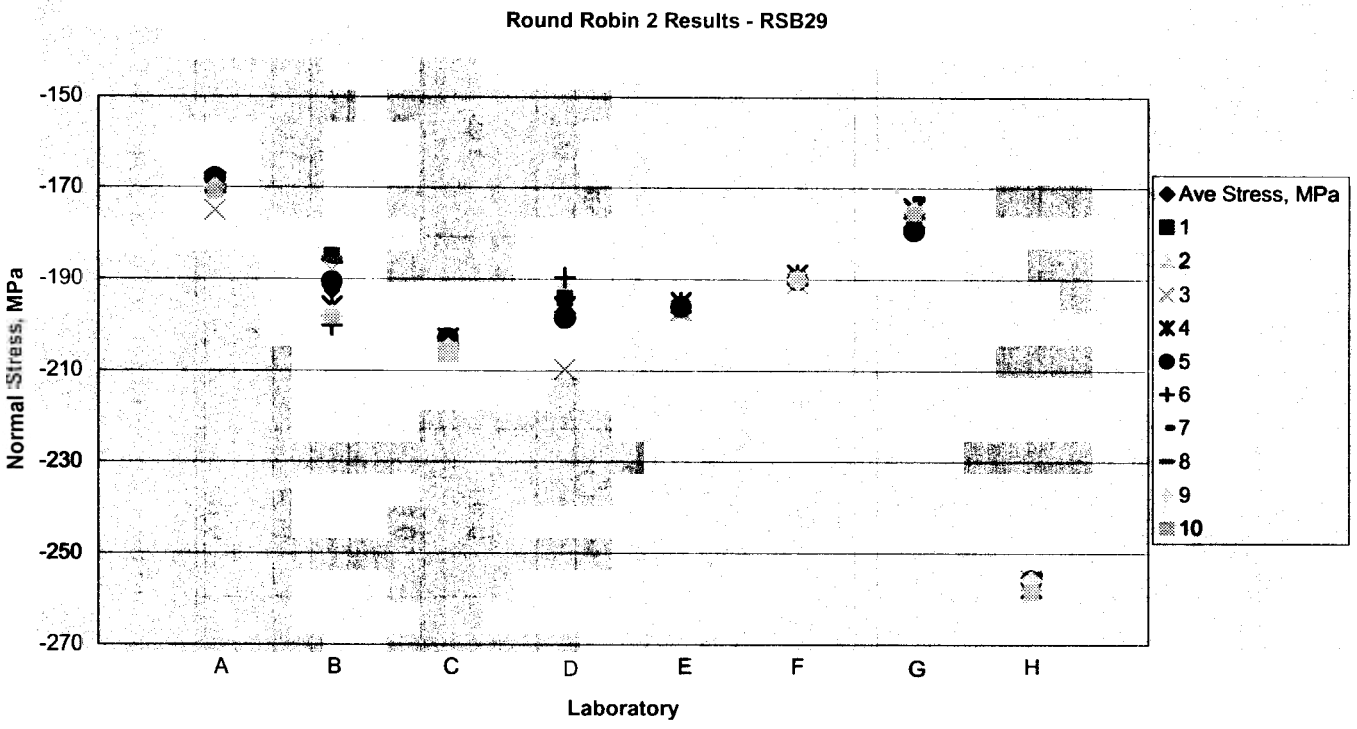


Fig 10: XRD Residual Stress measurements conducted on the same 7010 Al specimen, showing the scatter from repeat measurements and the average value for each Lab

Lab H was identified as having problems with their measurements and their results are excluded from the above analysis.

Table 13 gives the results from the 6082 aluminium alloy specimen. Each laboratory used the same equipment and tube set up as with the last sample. The 6082 alloy was more difficult to measure, because the sample exhibited large texturing effects which made the peak collection and analysis very difficult. Given the difficulty in collecting adequate data for analysis, there was no change in the 2θ range over which the Labs collected the data, however the count times used did generally increase (apart from lab H who decreased their collection time). Similarly, for all Labs, there was no change in the method used for correcting the data or analysing the peak. In this case, results from Lab A were disregarded as outliers and are not included in the calculations.

LAB	Stress Measurement, MPa											
	1	2	3	4	5	6	7	8	9	10	Mean	SD
A	-302	-216	-352	-278	-889*						-287 *	56
B	-72	-71									-72	1
C	-89	-89	-89	-92	-87	-91	-91	-89	-88	-89	-89	2
D	-89	-89	-81	-84							-86	4
E	-62	-60	-59	-58	-62	-63	-63	-66	-62	-64	-62	2
F	-61	-64	-62	-64	-65						-63	2
G	-137	-128	-129	-129	-130	-138					-132	4
H	-135	-136	-135	-133	-135						-135	1
Population Mean * = -90 ± 28 MPa												

* Results from Lab A were disregarded as outliers and are not included in the calculations

Table 13: XRD results on the heavily textured Al (2nd iteration)

Generally the number of psi tilts remained constant between samples, although lab E reduced theirs to only 2. The results appear to show a lot more scatter between laboratories than seen with the quenched 7010 Al block. Laboratory repeatability is generally good, although Lab A does show very large scatter, and measurement number 5 is considerably different than any of the others. The laboratory did report that usually they would not measure on such a textured material, and as an outlier, it will be excluded from subsequent statistical analyses.

Results from the second iteration generally show good repeatability with more reduced scatter compared with the first iteration – but the effect of material variability has been removed by using the same sample for all laboratories. The exercise has highlighted significant problems with a couple of the Labs whose measurements were considerably different than the majority reported.

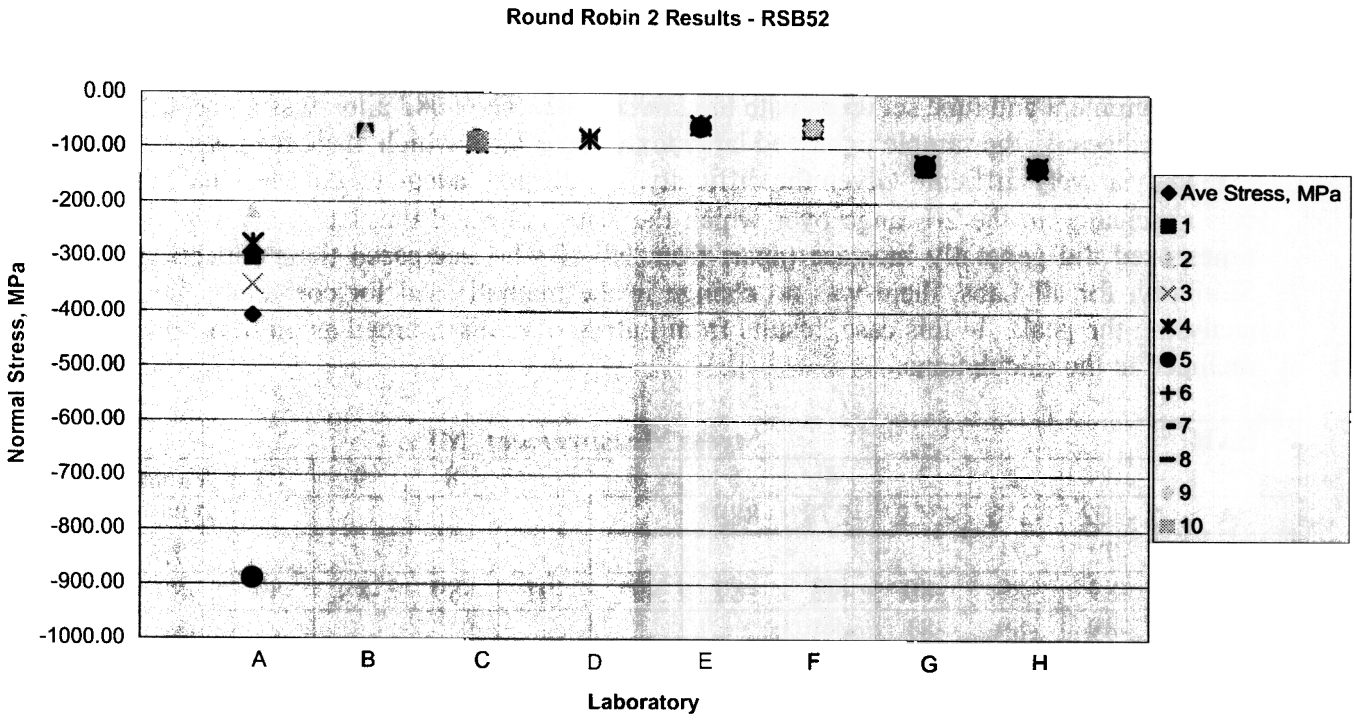


Fig 11 XRD Residual Stress measurements conducted on the 6082 alloy, showing the scatter from repeat measurements and the average value for each laboratory

4.3 Comparison of first and second iteration XRD results

Only the quenched 7010 aluminium alloy was examined in both iterations of the exercise, and the results are summarised in the table below.

1st Iteration			2nd Iteration		
Lab ID	**Lab Mean (MPa)**	**Dev. from pop mean (MPa)**	**Lab ID**	**Lab Mean (MPa)**	**Dev. from pop mean (MPa)**
A	**-187**	-8	**F**	**-190**	7
B	**-202**	-23	**E**	**-196**	1
C	**-186**	-7	**D**	**-197**	0
D	**-204**	-25	**A**	**-170**	27
E	**-179**	0	**C**	**-204**	-7
F	**-172**	7			
G	**-180**	-1	**B**	**-192**	5
H	**-171**	8	**G**	**-176**	21
I					
J	**-160**	19	**H**	**-257**	-60
K	**-151**	28			
Population mean = -179 ± 20 MPa			**Population mean = -197 ± 25 MPa ..... excl Lab H = -188 ± 12 MPa**		

Table 14: Comparison of the data from the two iterations on the quenched Al sample

The mean value from the first iteration is slightly lower than that measured in the second iteration but the standard deviation and scatter in the data is reduced from ± 20 MPa to ± 12 MPa. This improvement is likely to be due to a combination of factors including the elimination of material variability and improved measurement practice. Only 2 organisations (identified as D,A and J,H) failed to show real improvements in the quality of the measurements.

Results from this exercise, in addition to extensive sensitivity parameter tests carried out elsewhere [1], have been used to develop an *NPL Measurement Good Practice Guide on the Measurement of Residual Stresses by X-ray Diffraction* [2].

5 HOLE DRILLING RESULTS

Eight organisations were involved in the hole drilling study, although not all laboratories carried out every measurement. As with the XRD exercise, each participant was asked to perform measurements on the spring steel sample (in the as-received and shot peened condition) and the heat-treated 7010 aluminium sample, thus giving a total of three stress states. Measurements were carried out at the same locations as the XRD, but on different samples although some reference XRD was obtained on the hole drilling specimens for a direct comparison between the techniques on the same material and at the same location.

The purpose of this first iteration was to allow the organisations to carry out the measurements according to their individual procedures. Parameters such as gauge type and direction were not specified, and consequently it is impossible to directly compare the individual strain values ε_1, ε_2 and ε_3 from different laboratories. General observations however can be made.

It should be noted that Lab 8 did not carry out any measurements on the spring steel sample. Lab 2 made measurements at only one location on the steel sample; Labs 3, 6 and 7 each carried out 2 measurements on the as-received steel, and in the case of Lab 6, on the shot-peened sample also. Participants were asked to measure the residual stress at three pre-defined locations on the shot-peened and as-received sides of the steel, and at two locations on the aluminium, as shown previously in Figure 1. Equipment and experimental details are given in Table 15 below.

5.1 Equipment Details

Lab No.	Gauge type	Drill dia (mm)	No of incre-ments	Depth increment (mm)	Strain logger	Analysis technique
1	CEA-06-062-UM-120	1.8	16	0.1 (then 0.2)	MG P3500	EUS
2	CEA-06-062-UL-120	1.58	12	0.125	Tinsley 8692	Integral
3	CEA-06-062-UL-120	1.6	9	0.13 (then 0.25)	MG P3500	Basic/Blind hole
4	CEA-06-062-UL-120	1.2 + 0.8 eccentric	11	0.127	MG P3500	Integral
5	CEA-06-062-UL-120	1.57	9	0.25	MG P3500	EUS
6	CEA-06-062-UL-120	?	8	0.125	?	Integral
7	CEA-06-062-UL-120	1.6	16	0.1	MG P3500	EUS
8	CEA-06-062-UL-120	1.6		0.02	MG P3500	EUS

Table 15: Details of the Hole Drilling equipment used in the first iteration

Despite the range of residual stress strain gauge rosettes, gauge manufacturers and sizes available, all laboratories used gauges supplied by Measurements Group, and all but Lab 1 used the CEA-06-062-UL-120 gauge type. Lab 1 used the UM gauge of the same size, which has a slightly higher strain sensitivity, thus their raw strain gauge readings would be expected to be higher. The drill diameter used was typically ~1.6mm, although Lab 1 used a slightly larger drill diameter and Lab 4 used a set-up with a 1.2mm diameter drill and an 0.4mm offset and orbital drilling. The drill/hole size also has implications for the magnitude of the strain readings. All participants used incremental depth drilling although the number of depth increments varied from 8-16. Typical depth increments close to the surface were in the range 0.1-0.125mm. A limited range of strain gauge instrumentation was also used.

In the first iteration Lab 3 returned a single value for the residual stresses based on the basic calculation at full depth. Labs 1, 5, 7 and 8 used the *Equivalent Uniform Stress* (EUS) approach according to the procedure outlined in the Measurements Group Technical Note TN-503-5 [3]. Labs 2 and 4 used the Integral method for analysing their data. Further details of the various analysis techniques and the practical issues associated with making good quality residual stress measurements are presented in the NPL Measurement Good Practice Guide No. 52 [4].

5.2 First iteration

Results from the first iteration are included in Tables 16-22. For each organisation, only the readings from one measurement location are included for clarity (Pos A, D for the steel and Pos A for the Al specimen). Representative strain readings for each Lab and each material are also plotted in Figs 12-14. Although it is difficult to make direct comparisons of the strain readings from different laboratories, due to different strain gauges, drill and hole diameters, etc, the graphs provide an important basis for examining both the repeatability of individual organisations and an evaluation of subsequent stress analysis techniques. The tables include the strain readings for each gauge at each depth increment, and the calculated maximum and minimum principal stress values. In the cases where participants (Lab 4 for example) used the Integral method to calculate the residual stresses, the corresponding depth increments quoted for the stress calculations are included as an extra column.

5.2.1 Strain data

From the tables it is clear that there are large differences in the values of strain readings for the different laboratories, both in the magnitude and in the scatter in the separate measurements of ε_1, ε_2 and ε_3. This gives some indication of the quality of the measurement. Only Lab 1 used a different type of strain gauge, so the other results should be directly comparable. Some differences will still be evident because of the small differences in hole diameter and depth increments used.

It is interesting to note that some organisations reported large variations in the individual strain readings from the 3 gauges, whilst others were very repeatable. These large differences are likely to be caused by experimental errors and the results quoted should be treated with some caution. In particular the results for Lab 6 for the as-received spring steel were considerably different than any of the others and are excluded from Fig 12 and the analysis of the data for clarity.

AS RECEIVED STEEL (POS A)						SHOT PEENED STEEL (POS D)						QUENCHED AL (POS A)					
Z (mm)	SG1 (με)	SG2 (με)	SG3 (με)	σ_{min} (MPa)	σ_{max} (MPa)	Z (mm)	SG1 (με)	SG2 (με)	SG3 (με)	σ_{min} (MPa)	σ_{max} (MPa)	Z (mm)	SG1 (με)	SG2 (με)	SG3 (με)	σ_{min} (MPa)	σ_{max} (MPa)
0.1	-8	-7	-5	47	66	0.1	100	113	110	-975	-863	0.1	55	60	66	-185	-163
0.2	-10	-11	-10	36	41	0.2	215	239	238	-920	-832	0.2	128	133	155	-193	-167
0.3	-15	-16	-17	37	40	0.3	297	332	332	-794	-716	0.3	233	250	253	-198	-186
0.4	-21	-22	-23	37	39	0.4	337	380	388	-663	-594	0.4	335	356	369	-207	-194
0.5	-28	-29	-28	38	39	0.5	363	409	416	-563	-506	0.5	435	449	466	-208	-199
0.6	-30	-33	-35	36	39	0.6	380	430	440	-499	-447	0.6	534	554	570	-214	-205
0.7	-33	-37	-40	35	39	0.7	392	444	459	-455	-408	0.7	612	629	644	-213	-206
0.8	-36	-39	-43	34	38	0.8	399	454	465	-420	-377	0.8	663	677	693	-209	-203
0.9	-36	-41	-45	33	37	0.9	407	462	476	-401	-360	0.9	724	736	745	-210	-207
1	-36	-42	-46	31	36	1	410	468	481	-386	-346	1	761	774	778	-210	-207
1.1	-37	-42	-47	31	36	1.1	413	472	485	-375	-337	1.1	798	806	807	-211	-209
1.2	-37	-43	-47	30	35	1.2	416	474	488	-367	-331	1.2	821	825	825	-210	-209
1.4	-37	-42	-47			1.4	418	478	492			1.4	859	856	849		
1.6	-37	-44	-49			1.6	420	481	494			1.6	878	869	854		
1.8	-39	-45	-50			1.8	421	483	497			1.8	879	866	847		
2	-39	-47	-51	32	36	2	421	484	499	-363	-329	2	880	863	840	-216	-211

Table 16: Lab 1 – Example strain and stress data for measurements on the 3 materials (1 position – first iteration)

AS RECEIVED STEEL (POS A)							SHOT PEENED STEEL (POS D)							QUENCHED AL (POS A)						
Z (mm)	SG1 (με)	SG2 (με)	SG3 (με)	Z (mm)	σ_{min} (MPa)	σ_{max} (MPa)	Z (mm)	SG1 (με)	SG2 (με)	SG3 (με)	Z (mm)	σ_{min} (MPa)	σ_{max} (MPa)	Z (mm)	SG1 (με)	SG2 (με)	SG3 (με)	Z (mm)	σ_{min} (MPa)	σ_{max} (MPa)
0.127	0	4	4	0.128	-12	-31	0.127	53	54	34	0.128	-557	-413	0.127	54	43	60	0.128	-269	-254
0.254	3	9	2	0.257	-7	12	0.254	119	100	74	0.257	-565	-371	0.254	148	113	158	0.257	-224	-215
0.381	4	8	0	0.385	-17	32	0.308	201	167	119	0.385	-494	-362	0.308	220	165	234	0.385	-253	-252
0.508	9	7	-6	0.513	-16	32	0.508	250	205	155	0.513	-294	-246	0.508	322	237	333	0.513	-237	-230
0.635	10	9	-9	0.641	11	36	0.635	287	236	179	0.641	-155	-131	0.635	386	287	394	0.641	-204	-183
0.762	10	7	-13	0.770	10	28	0.762	308	253	193	0.770	-112	-91	0.762	454	339	451	0.770	-259	-232
0.889	11	5	-15	0.898	12	33	0.889	326	268	205	0.898	-115	-120	0.889	510	390	501	0.898	-280	-264
1.016	11	2	-18	1.026	33	52	1.016	335	280	214	1.026	4	-29	1.016	554	431	541	1.026	-296	-287
1.143	11	2	-20	1.154	15	47	1.143	339	286	218	1.154	10	-19	1.143	587	462	572	1.154	-289	-284
1.27	12	2	-22	1.283	29	63	1.27	343	290	222	1.283	-9	-19	1.27	608	483	591	1.283	-267	-260
1.397	12	1	-23				1.397	345	292	223				1.397	622	499	603			

Table 7 Lab 2 Example strain and stress data fo measurements th terials positio first iteratio ı)

AS RECEIVED STEEL (POS A)						SHOT PEENED STEEL (POS D)						QUENCHED AL (POS A)					
Z (mm)	SG1 (με)	SG2 (με)	SG3 (με)	σ_{min} (MPa)	σ_{max} (MPa)	Z (mm)	SG1 (με)	SG2 (με)	SG3 (με)	σ_{min} (MPa)	σ_{max} (MPa)	Z (mm)	SG1 (με)	SG2 (με)	SG3 (με)	σ_{min} (MPa)	σ_{max} (MPa)
0.13	9	9	10			0.13	30	34	27			0.13	18	19	13		
0.25	6	3	5			0.25	106	120	92			0.25	80	81	72		
0.5	2	-4	-3			0.5	174	198	156			0.5	225	232	217		
0.75	-2	-10	-10			0.75	198	228	176			0.75	350	377	344		
1	-5	-13	-15	18	29	1	207	243	186	-263	-203	1	442	479	442	-183	-170
1.25	-6	-15	-17			1.25	212	248	188			1.25	490	532	493		
1.5	-7	-15	-19			1.5	214	252	190			1.5	510	552	516		
1.75	-7	-16	-20			1.75	216	253	191			1.75	515	557	524		
2	-7	-16	-20			2	216	254	192			2	515	557	524		

ble Lab Example strain and stress data fo measurements th 3 materials (position first it ration

AS RECEIVED STEEL (POS A)							SHOT PEENED STEEL (POS D)							QUENCHED AL (POS x)						
Z (mm)	SG1 (με)	SG2 (με)	SG3 (με)	Z (mm)	σ_{min} (MPa)	σ_{max} (MPa)	Z (mm)	SG1 (με)	SG2 (με)	SG3 (με)	Z (mm)	σ_{min} (MPa)	σ_{max} (MPa)	Z (mm)	SG1 (με)	SG2 (με)	SG3 (με)	Z (mm)	σ_{min} (MPa)	σ_{max} (MPa)
0.13	0	0	-4	0.06	0	33	0.13	92	84	91	0.06	-864	-777	0.13	89	74	80	0.06	-264	-219
0.25	-4	-6	-11	0.19	25	43	0.25	210	196	218	0.19	-769	-666	0.25	202	174	178	0.19	-211	-190
0.38	-10	-14	-20	0.38	33	44	0.38	278	260	290	0.38	-130	-120	0.38	313	275	272	0.38	-189	-164
0.51	-14	-19	-26				0.51	308	290	322				0.51	413	366	353			
0.64	-16	-23	-32	0.64	14	29	0.64	325	309	342	0.64	68	98	0.64	495	441	418	0.64	-165	-134
0.76	-18	-25	-36				0.76	336	323	356				0.76	562	501	467			
0.89	-18	-25	-40				0.89	344	331	364				0.89	612	546	501			
1.02	-20	-31	-41	1.02	34	47	1.02	348	336	370	1.02	25	42	1.02	648	579	525	1.02	-157	-112
1.14	-21	-32	-45				1.14	351	339	374				1.14	675	603	539			
1.27	-22	-34	-47				1.27	353	341	376				1.27	693	618	546			
1.4	-23	-33	-49				1.4	354	343	378				1.4	704	548	548			

Table 19: Lab 4 Example strain and stress data for measurements on the 3 materials (1 position – first iteration)

AS RECEIVED STEEL (POS A)						SHOT PEENED STEEL (POS D)						QUENCHED AL (POS A)					
Z (mm)	SG1 (με)	SG2 (με)	SG3 (με)	σ_{min} (MPa)	σ_{max} (MPa)	Z (mm)	SG1 (με)	SG2 (με)	SG3 (με)	σ_{min} (MPa)	σ_{max} (MPa)	Z (mm)	SG1 (με)	SG2 (με)	SG3 (με)	σ_{min} (MPa)	σ_{max} (MPa)
0.25	-2	-2	-4	9	18	0.25	90	131	265	-1446	-635	0.25	108	143	136	-183	-135
0.5	-7	-8	-13	16	26	0.5	144	221	441	-1072	-490	0.5	236	318	303	-186	-137
0.75	-10	-19	-22	17	29	0.75	160	251	490	-805	-388	0.75	348	466	445	-188	-142
1	-13	-20	-24	18	26	1	167	265	515	-696	-349	1	421	566	546	-193	-147
1.25	-14	-23	-26	18	26	1.25	171	274	523	-641	-337	1.25	453	622	453	-180	-114
1.5	-14	-23	-26			1.5	175	280	530	-615	-350	1.5	464	647	619		
1.75	-14	-24	-26			1.75	176	282	532			1.75	462	656	624		
2	-15	-26	-27	18	27	2	176	283	533	-615	-350	2	454	649	622	-195	-148
2.25	-15	-26	-28			2.25	177	285	535			2.25	449	654	623		

Table 20: Lab 5 – Example strain and stress data for measurements on the 3 materials (1 position – first iteration)

AS RECEIVED STEEL (POS A)						SHOT PEENED STEEL (POS D)						QUENCHED AL (POS A)					
Z (mm)	SG1 (με)	SG2 (με)	SG3 (με)	σ_{min} (MPa)	σ_{max} (MPa)	Z (mm)	SG1 (με)	SG2 (με)	SG3 (με)	σ_{min} (MPa)	σ_{max} (MPa)	Z (mm)	SG1 (με)	SG2 (με)	SG3 (με)	σ_{min} (MPa)	σ_{max} (MPa)
0.12	17	-106	-60	-267	519	0.12	100	132	119	-1066	-777	0.12	98	95	122	-346	-271
0.25	16	-118	-22	-140	-65	0.25	191	223	209	-527	-554	0.25	204	209	227	-200	-226
0.5	8	-140	6	-53	7	0.5	214	249	242	-32	-45	0.5	364	344	398	-184	-144
0.75	-17	-172	5	-7	67	0.75	259	301	282	-200	-168	0.75	468	465	492	-118	-152
1	-22	-154	-17	71	7	1	282	322	316	-229	-237	1	510	523	507	-106	-112
1.25	-35	-151	-25	41	46	1.25	294	339	378	-391	-306	1.25	512	538	523	-123	-109
1.5	-25	-165	-18	-95	46	1.5	304	349	325	-176	-188	1.5	511	538	523	-155	-150
2	-34	-174	-3	-54	68	2	308	352	332	-306	-285	2	500	520	513	-137	-140

Table 21 Lab 6 E: le strai d stress data fo measurements the materials positio first iteration)

AS RECEIVED STEEL (POS A)						SHOT PEENED STEEL (POS D)						QUENCHED AL (POS A)					
Z (mm)	SG1 (με)	SG2 (με)	SG3 (με)	σ_{min} (MPa)	σ_{max} (MPa)	Z (mm)	SG1 (με)	SG2 (με)	SG3 (με)	σ_{min} (MPa)	σ_{max} (MPa)	Z (mm)	SG1 (με)	SG2 (με)	SG3 (με)	σ_{min} (MPa)	σ_{max} (MPa)
0.1	6	4	3	-100	-60	0.1	5	6	3	-100	-42	0.1	26	27	24	-95	-87
0.2	-3	-5	-4	19	36	0.2	53	53	59	-462	-415	0.2	76	70	67	-117	-106
0.3	-17	-16	-13	65	80	0.3	112	113	122	-589	-546	0.3	156	145	139	-153	-140
0.4	-23	-20	-16	60	76	0.4	164	165	175	-608	-574	0.4	219	203	200	-159	-148
0.5	-28	-24	-19	56	73	0.5	186	185	198	-543	-509	0.5	301	277	270	-171	-157
0.6	-32	-28	-20	50	69	0.6	200	198	215	-492	-456	0.6	364	328	321	-164	-148
0.7	-36	-31	-21	47	67	0.7	209	206	224	-447	-415	0.7	423	378	368	-169	-151
0.8	-39	-33	-21	43	64	0.8	214	211	232	-417	-384	0.8	476	417	406	-177	-156
0.9	-40	-35	-21	40	61	0.9	219	215	236	-393	-363	0.9	522	449	440	-181	-158
1	-43	-38	-22	40	62	1	223	219	241	-379	-350	1.0	555	472	459	-180	-156
1.1	-44	-38	-22	39	60	1.1	223	222	243	-366	-340	1.1	580	487	476	-179	-154
1.2	-45	-40	-21	37	60	1.2	228	223	246	-361	-333	1.2	597	496	485	-182	-156
1.4	-45	-40	-21			1.4	228	224	247			1.3	610	500	490	-181	-153
1.6	-47	-40	-21	39	59	1.6	231	225	249	-348	-322	1.4	624	507	494		
1.8	-47	-40	-21			1.8	230	225	249			1.5	634	512	497		
2	-48	-40	-22			2	230	225	250			1.6	640	512	497		

Table 22 Lab 7 Exampl strain nd stress data for measurements the 3 materials position first iteratio ı)

The hole drilling results are considered in two parts, via examination of the raw strain gauge data and by the reported stress values. The former analysis should give information on the measurement procedure and experimental practice; the latter will focus on the analysis techniques used.

Table 23 shows the summary of the strain readings for each laboratory and material, taken at an arbitrary depth of 0.5 mm. The mean value is taken from the 3 separate strain gauge readings, and the range is the maximum scatter in the data, expressed in microstrain and as a percentage of the mean reading. The results are ranked in Table 24 to compare and identify how individual laboratories were performing.

As received spring steel									
Lab ID	Pos A			Pos B			Pos C		
	Mean (με)	Range (με)	Range (%)	Mean (με)	Range (με)	Range (%)	Mean (με)	Range (με)	Range (%)
1	-28	1	4	-19	15	79	-10	4	40
2	-3	15	500						
3	-2	6	300	1	10	1000			
4	-20	12	60	-17	2	12	-1	8	800
5	-9	6	66	-18	3	17	-25	4	16
6	42	148	400	-88	24	27			
7	-24	9	38				-18	16	89

Shot peened spring steel									
Lab ID	Pos D			Pos E			Pos F		
	Mean (με)	Range (με)	Range (%)	Mean (με)	Range (με)	Range (%)	Mean (με)	Range (με)	Range (%)
1	396	53	13	381	25	7	465	19	4
2	203	95	47						
3	176	42	23	101	6	6	103	80	78
4	307	32	10	308	29	9	328	20	6
5	269	297	110	288	36	13	230	154	67
6	235	35	15	297	214	72			
7	190	13	7	181	6	3			

Quenched 7010 Al						
Lab ID	Pos A			Pos B		
	Mean (με)	Range (με)	Range (%)	Mean (με)	Range (με)	Range (%)
1	450	31	7	399	73	18
2	297	96	32			
3	225	15	7	247	79	32
4	377	60	16	371	27	7
5	286	82	29	235	21	9
6	369	54	15	289	270	93
7	283	31	11	287	12	4

Table 23: Summary of strain readings at a nominal 0.5mm depth, for all Laboratories and materials

MAGNITUDE		**LARGE**						**small**
	As received steel, Pos A	1	7	4	5	3	2	6
	Shot peened steel, Pos D	1	4	5	6	2	7	3
	Quenched Al, Pos A	1	4	6	2	5	7	3

RANGE		**small (best)**						**LARGE (worst)**
	As received steel, Pos A	1	3	5	7	4	2	6
	Shot peened steel, Pos D	7	4	6	3	1	2	5
	Quenched Al, Pos A	3	7	1	6	4	2	5

RANGE %		**small (best)**						**LARGE (worst)**
	As received steel, Pos A	1	7	4	5	3	6	2
	Shot peened steel, Pos D	7	4	1	6	3	2	5
	Quenched Al, Pos A	1	3	7	6	4	5	2

Table 24: Performance ranking of Hole Drilling Laboratories according to the magnitude of the strain readings, and the range (scatter)

Although the ranking and performance metrics in Tables 23 and 24 are somewhat arbitrary, they do give some insight into which laboratories are performing well and which have problems. The data discussed so far does not involve any calculation of stress, but are based solely on the raw strain data, which is thus an indication of the quality and reliability of the experimental set-up and measurement practice.

Representative strain data for all the materials examined are given in Figs 12-14. The range of strain readings measured for the as-received steel samples was low, with the exception of Lab 6, which clearly had some problems (the results of which have been ignored in the subsequent analysis of the data). Labs 1, 3 and 4 give good repeatability, although the results for position C of Lab 5 was a little lower than the others and the ε_3 values for both positions of Lab 7 a little higher than ε_1 and ε_2. The magnitudes of the mean strain readings were reasonably consistent; most were slightly negative and showed a similar profile with depth. With the low strain readings any experimental errors or uncertainties in the strain measurement is likely to have a large influence on the quality of the stress data produced.

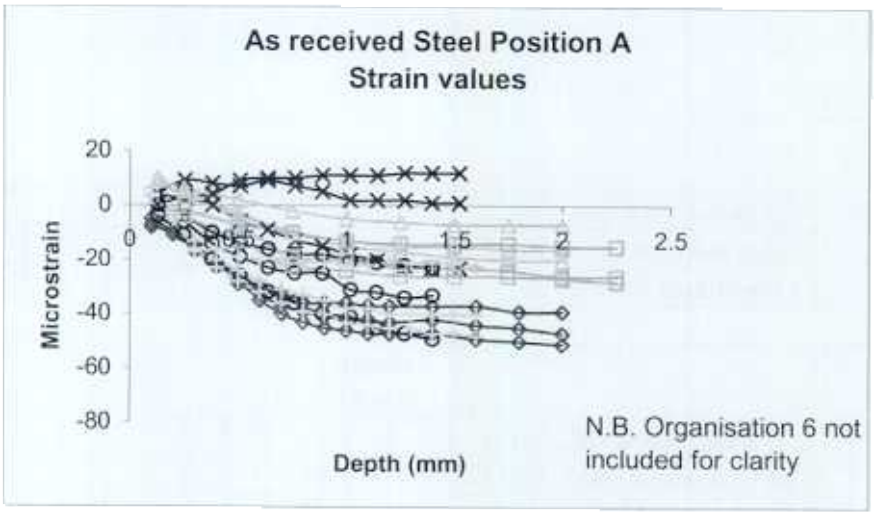


Fig 12: Strain readings from all laboratories (as–received spring steel)

The strain readings for the shot peened steel are considerably higher than the as-received condition and the strain profile (Fig 13) is very different. There is a huge variation between laboratories in the magnitude of strains reported. Lab 1 reports the highest strain readings for all the materials examined, but this is expected because they used the "UM" type gauge which has a higher strain sensitivity than the "UL" gauge used by the other laboratories. The large difference in magnitude between the other Labs is not easy to explain, although there will be some effect of using different hole and drill sizes. As an example, Lab 7 shows excellent repeatability and low scatter in the individual strain readings, but the magnitude of the strain readings are considerably lower than Lab 4. Labs 1, 3, and 4 also showed excellent repeatability with low scatter. Again Labs 2, 5 and 6 appear to have problems achieving stable readings, although the observed profiles are more consistent than with the as-received steel.

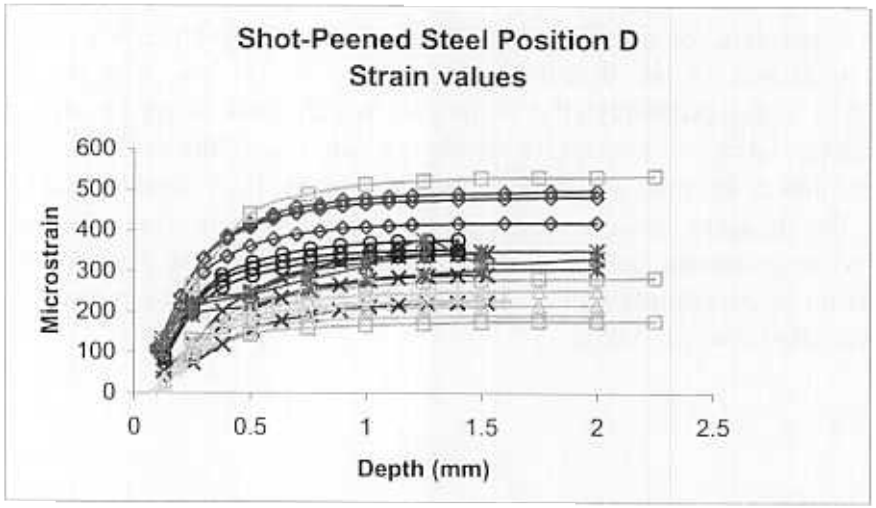


Fig 13: Strain readings from all laboratories (shot peened spring steel)

Only two measurements were carried out on the aluminium samples, on opposite sides in the centre of the block Most of the laboratories showed reasonable repeatability (Fig 14). Generally the magnitude of the strain gauge readings was the highest of the three materials tested. Lab 5 showed a slight anomaly in one plot, and Lab 6 again had the largest range of strain readings, with a maximum scatter approaching 300με, for Position B.

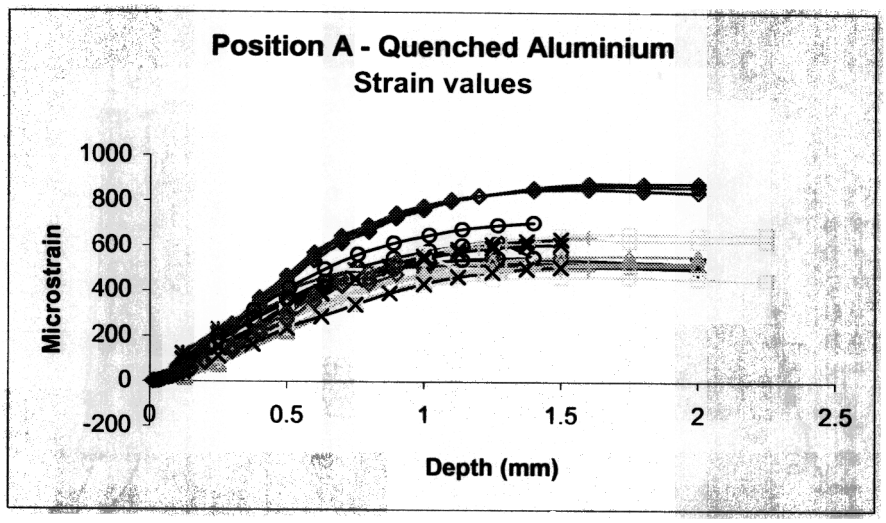


Fig 14: Strain readings from all laboratories (quenched aluminium)

Figs 15-17 show further strain measurements from individual laboratories for each material, highlighting some of the clear differences in the quality and repeatability of the data.

General conclusions on the strain measurements show that reasonable repeatability was achieved for most laboratories for all 3 stress states examined (N.B. This could not be assessed for Lab 2 due to lack of repeat measurements). There was potential for at least two laboratories to improve their measurement technique. The large variation in both the magnitude and scatter in the strains measured by the different participants highlights the scope for improvements in measurement practice.

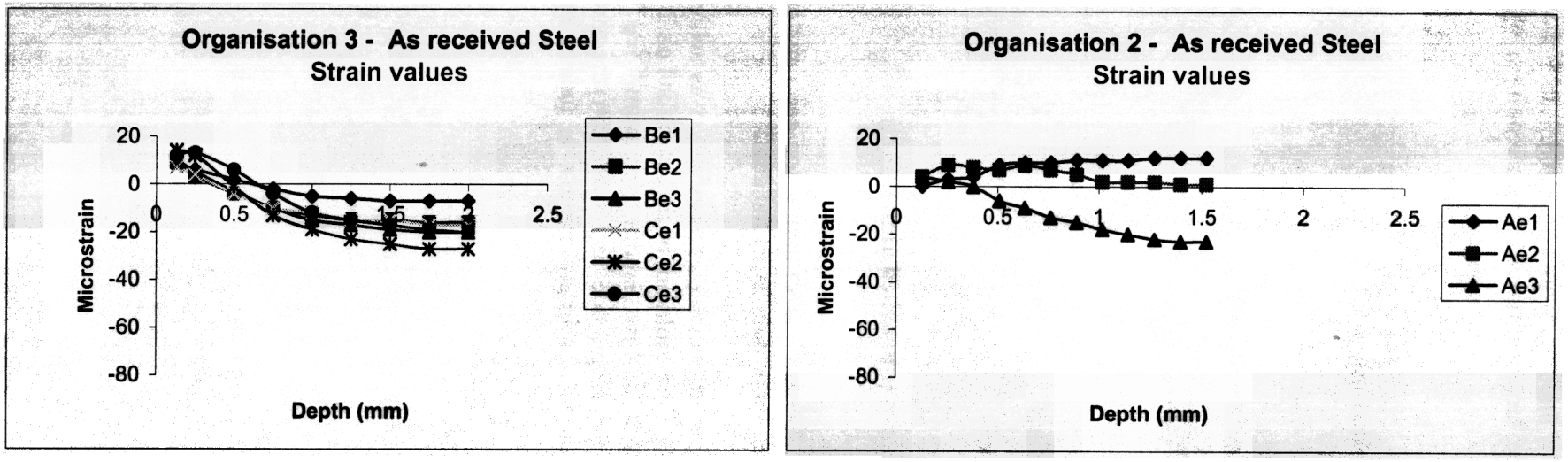


Fig 15: Representative (good and variable) strain data for the as-received spring steel

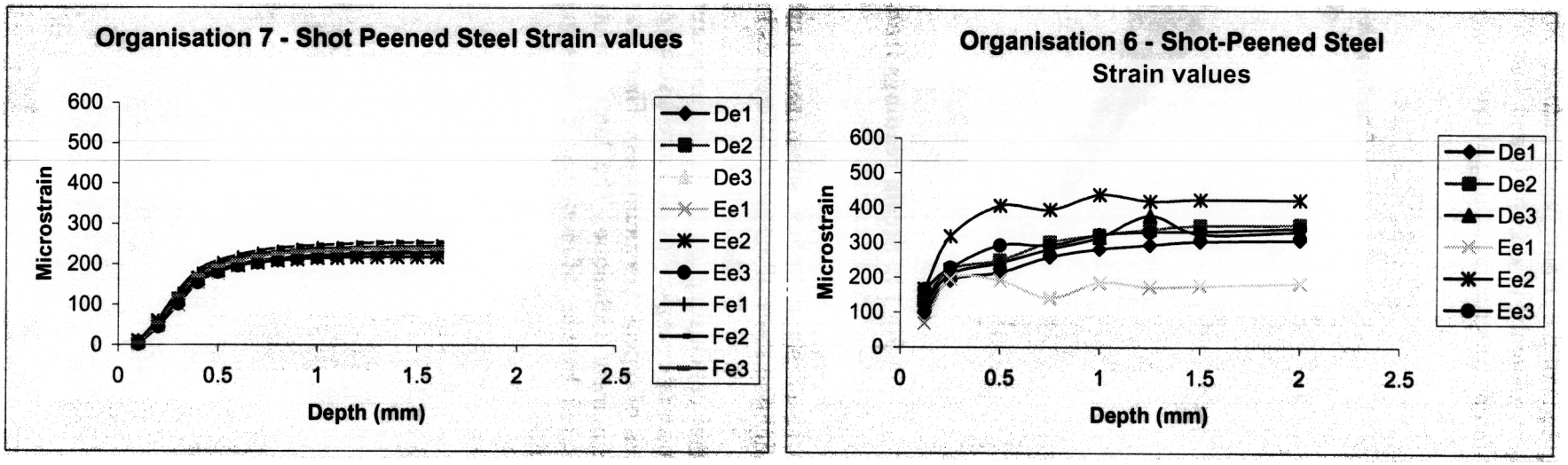


Fig 16: Representative (good and variable) strain data for the as-received spring steel

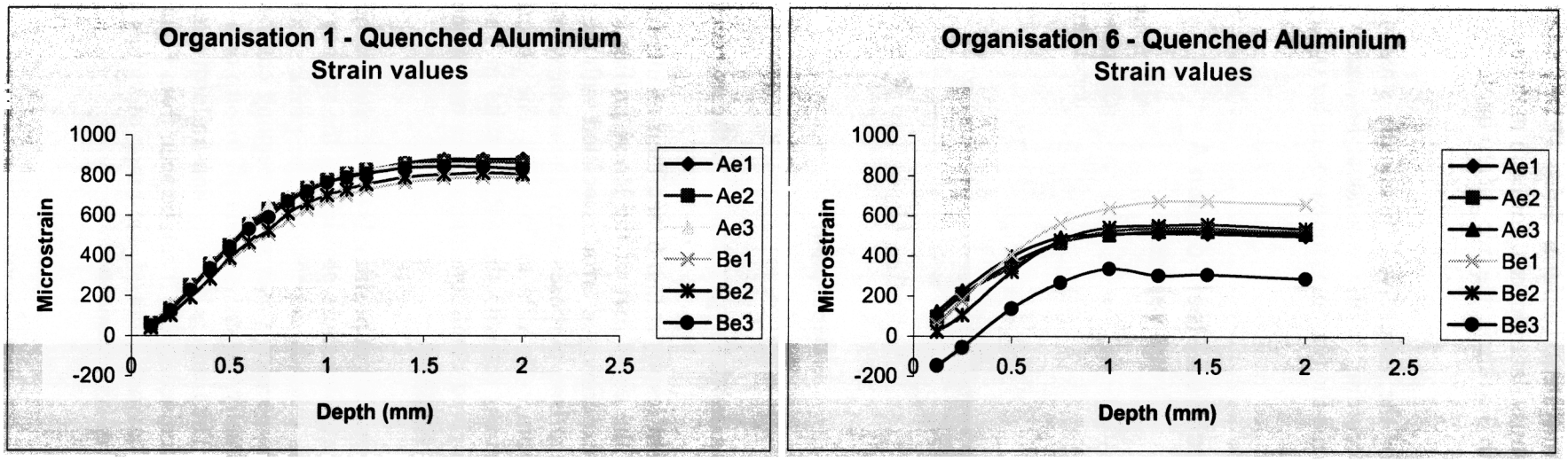


Fig 17: Representative (good and variable) strain data for the quenched aluminium specimen

5.2.2 Stress data

Consider now the stress values reported. The laboratories in this exercise used a number of data analysis techniques, including the Equivalent Uniform Stress (EUS) Method and the Integral Method. Representative plots of the stress data reported for each material are given in the figures below. No graphs are available for Lab 3 as their practice was to quote a single stress values at a given depth.

Figure 18 shows the data reported for the as-received (nominally stress-free) spring steel. The stress values have been calculated according to the individual laboratory's analysis technique. Each colour represents one laboratory and the two lines for each are for σ_{max}, and σ_{min}.

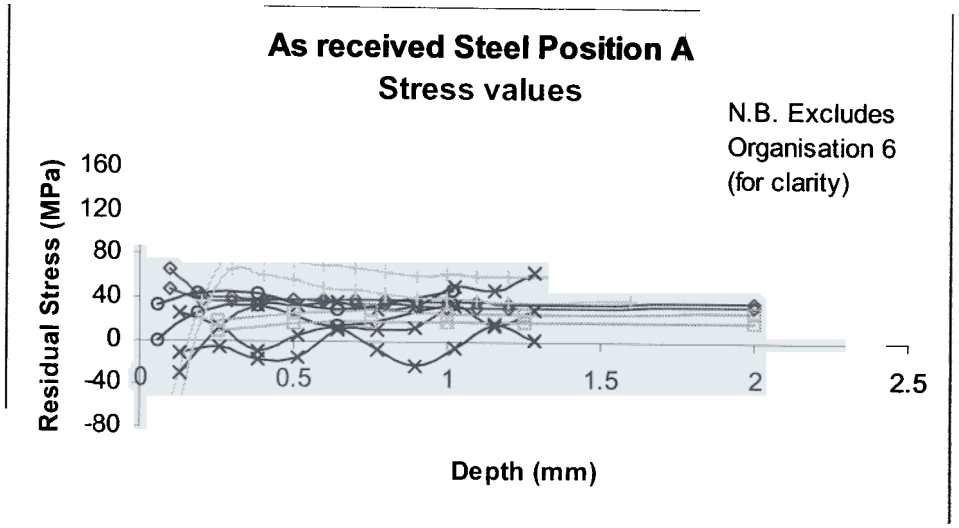


Figure 18: Profile of residual stress vs depth for position A on the as-received steel.

The only Lab with significantly different results is Lab 6, and their results have been excluded for clarity. There is some uncertainty in the early part of the stress profile (in the first few depth increments), but generally, within the experimental error associated with the technique, the results are in reasonable agreement. For comparison purposes only, the mean values of residual stresses reported at the 0.5mm depth range from -15 MPa to 75 MPa. The general trend from all the measurements shows a slight tensile stress (cf with the XRD results in Table 5, which give the mean value as 5 MPa). For the as-received condition, there does not appear to be a significant effect of using different data analysis techniques.

Figure 19 compares the residual stress profiles at position D on the shot-peened steel. The purpose of shot peening is to introduce a compressive stress profile into the surface of the specimen. The depth to which the compressive stress extends depends on the process conditions used, but is typically about 0.5mm for conventional peening (laser shock peening can be used to increase the depth of this layer significantly). Eventually the stress levels off to zero or a slight tensile stress to maintain equilibrium in the specimen. The result is a highly non-uniform stress field - and one that offers a greater challenge than the as-received steel. It can be seen from Figure 19 that only one or two profiles fit this expected stress behaviour. Indeed, the range of values and profiles obtained from the participants is remarkable and of some concern.

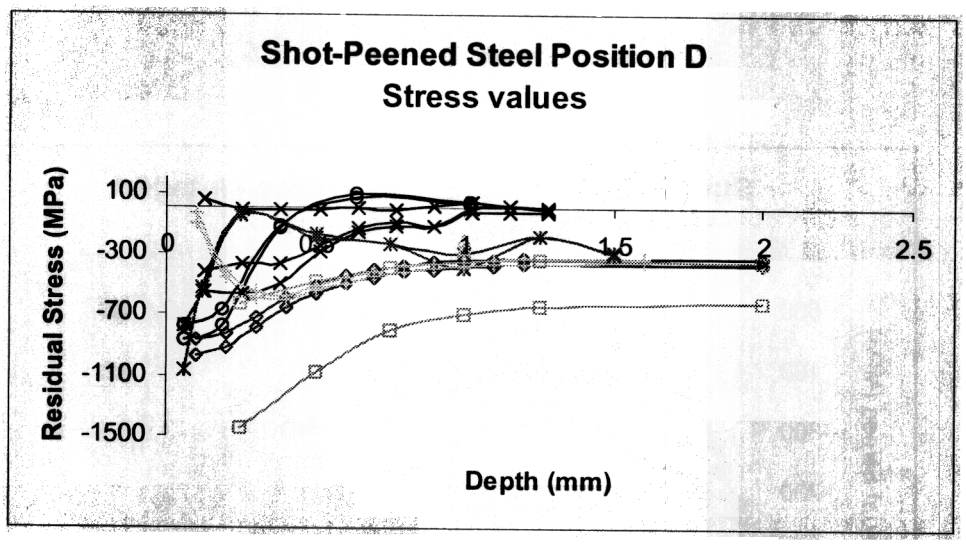


Figure 19: Profile of residual stress vs depth for position D on the shot-peened steel

As an indication of the scatter in these results, the range of stress quoted at 0.5mm is over 1100 MPa and there are clearly problems with this data set. In order to separate out the effect of the different analysis methods used, Figures 20 and 21 show the individual calculated stress profiles grouped according to the EUS and integral analysis methods .

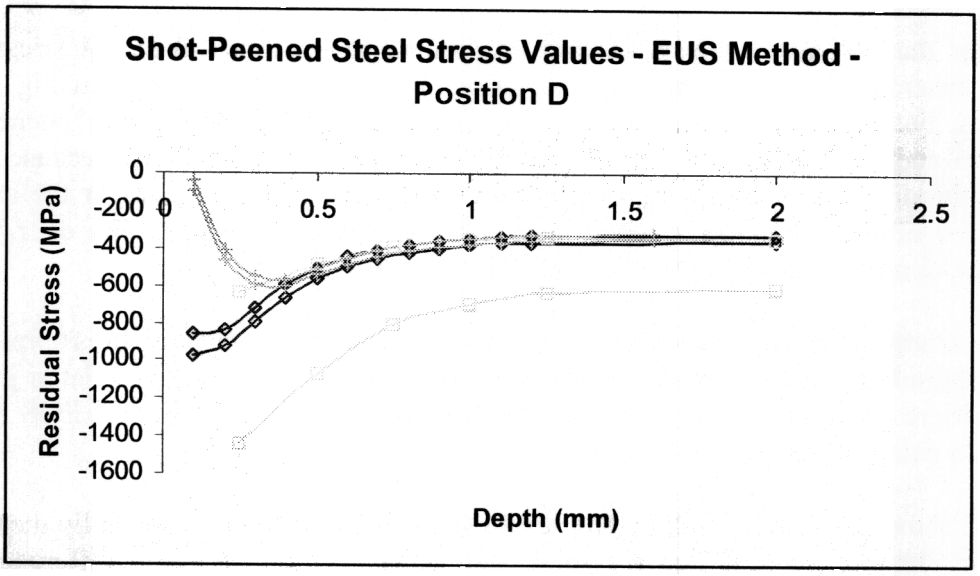


Figure 20: Profile of residual stress vs depth for position D on the shot-peened steel. ONLY THOSE LABORATORIES THAT USED THE EUS METHOD ARE SHOWN

The main conclusion that can be drawn from the above results is that the EUS stress profiles vary considerably between laboratories, particularly close to the surface, and non of the results show the expected profile for the shot peened material.

Consider now the equivalent figure for the Laboratories that used the Integral method.

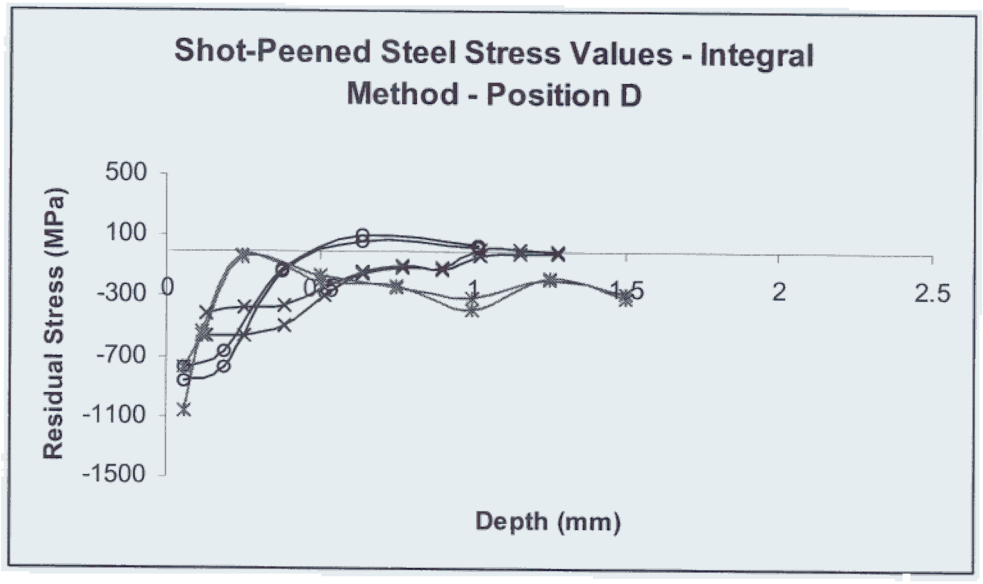


Figure 21: Profile of residual stress vs depth profiles for position D on the shot-peened steel. ONLY THOSE LABORATORIES THAT USED THE INTEGRAL METHOD ARE SHOWN

It is clear that the two analysis techniques produce significantly different stress profiles. The profiles generated by (different implementations of) the Integral method in Fig 21 show some variability but are much closer to the expected stress profile for a shot peened steel. Some validation and comparison of the different implementations is required because it is not clear whether the differences above are due to the experimental measurements or the analysis method itself. Two of the laboratories report near surface stresses of –800 MPa over the first depth increment, compared to –500 MPa for the XRD measurements.

There is strong evidence to recommend that for this highly non-uniform stress profile the Integral method should be used for analysing the data. This is highlighted in more detail in the following section where some of the original data supplied by laboratories using the EUS method will be reanalysed using the Integral approach.

Figure 22 shows the corresponding data for the quenched aluminium. Generally there is reasonable agreement between laboratories regarding the stress profile, but some differences in the first increment close to the surface. It is clear that for all cases examined the quality and accuracy of the strain data in the first few increments has an important effect on the results, as this is where the strain sensitivity is highest and the strain readings themselves are likely to be small and more susceptible to error.

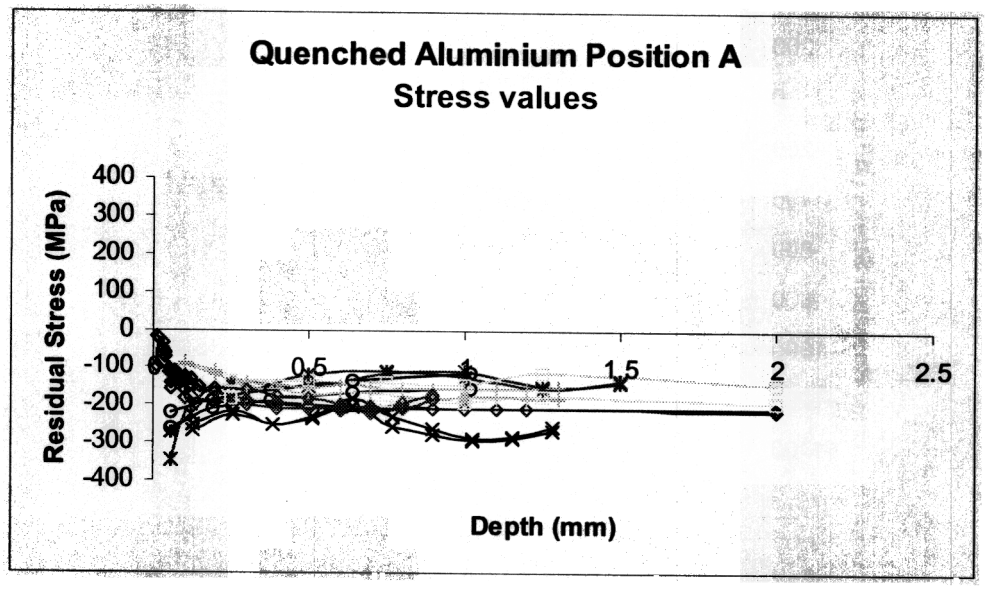


Figure 22: Profile of residual stress vs depth for position A on the heat-treated aluminium

For the quenched aluminium specimen, the near surface stresses reported vary from –100 MPa to –350 MPa. Lab 4, who carried out a series of measurements at very fine depth increments close to the surface (not included in the tables in this report), showed much lower values of compressive stress at the surface.

Results show a fairly constant compressive stress over the range of depths, but once again there is some disparity close to the surface. Lab 8, for example, shows a fairly steady increase in compressive stress from 0 to –200 MPa whilst Lab 4 has values of –250 to –150 MPa over the same range. For comparison, the overall spread in the data at 0.5mm depth is about 120MPa.

From these results it is clear that hole drilling, when applied with care, can be a repeatable and accurate method of measuring residual stress. The results on the as-received steel and heat-treated aluminium were in reasonable agreement, but severe problems have been highlighted with the analysis of data generated on the shot-peened steel.

5.2.3 Further Analysis of the results

To clarify the importance of using the appropriate analysis technique, three further studies were carried out.

In the first case, some of the Labs were asked to analyse the same set of raw strain data via their chosen technique, which would give a further comparison of the different analysis techniques. In the second case, some of the original EUS strain data was reanalysed via the Integral method, and thirdly, some of the original data was reanalysed by a second laboratory, using a different version of the Integral method software, to compare different implementations of the same analysis technique. Results are presented in Figs 23-25 below.

Analysis of the same strain data via all techniques .....

Two sets of shot-peened steel strain data were supplied to the laboratories that participated in the first exercise. Of those who returned the data, three used the Integral method and two used the EUS method. The data is presented in Figures 23 below.

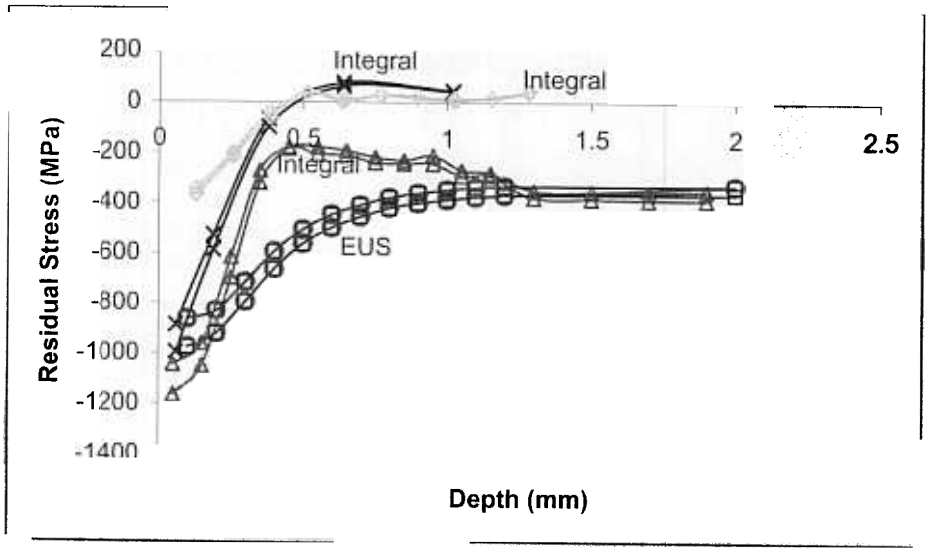


Figure 23: Profile of residual stress vs depth for a single set (Lab 1 data) of shot-peened steel strain data via all techniques

This confirms the earlier conclusion that for the non-uniform stress field present in the shot-peened steel, the choice of analysis is crucial for obtaining the correct stress profile, and that the Integral method should be used. It is interesting to note however, that in nearly all the profiles, the values of residual stress calculated in the first depth increment are very similar regardless of technique. There is some variation in the profiles generated using different Integral techniques in this set of data, which should be examined further. In all cases, probably the most important experimental factors are establishing the zero depth position (the point where the drill is in direct contact with the specimen surface) and the depth of the first increment.

Reanalysis of original strain data via the integral method .....

Some of the original shot-peened steel strain data generated by a Lab who had previously used the EUS method was reanalysed using the Integral method. Fig 24 shows the original (EUS) stress profiles generated for 3 sets of results, compared with the **same strain data** reanalysed using the Integral method, used by Lab 4.

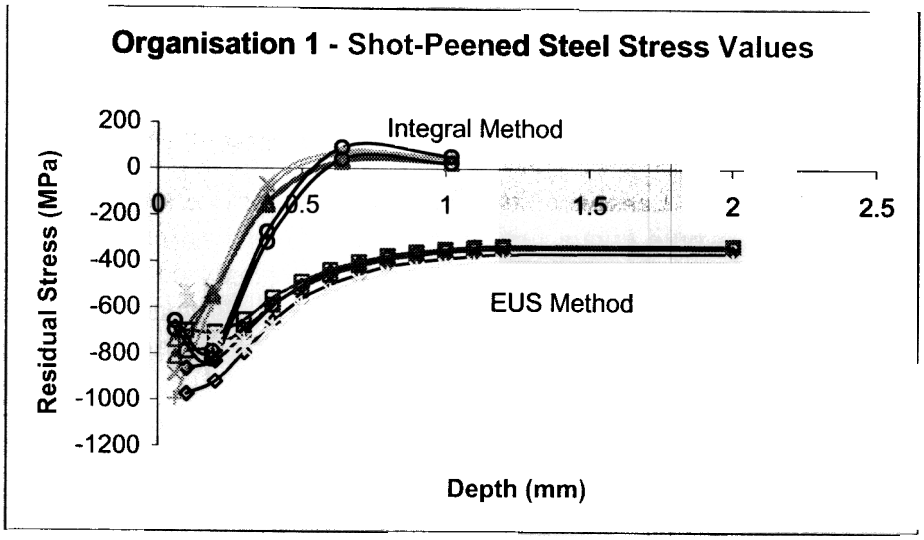


Figure 24: Profile of residual stress vs depth for 3 positions on the shot-peened sample for one organisation. Original results calculated via the EUS method are compared to Integral analysis.

Comparing different implementations of the Integral method .....

To compare different interpretations of the integral method, a single set of data was analysed by two labs using different software. The corresponding stress profiles for 2 measurement positions are given in Figs 25 and 26. Again the limitation of using the EUS analysis method for the shot peened specimen is apparent, and although the quality of the original data led to differences in the stress profiles for the 2 locations, both interpretations of the Integral technique gave almost identical stress profiles in each case.

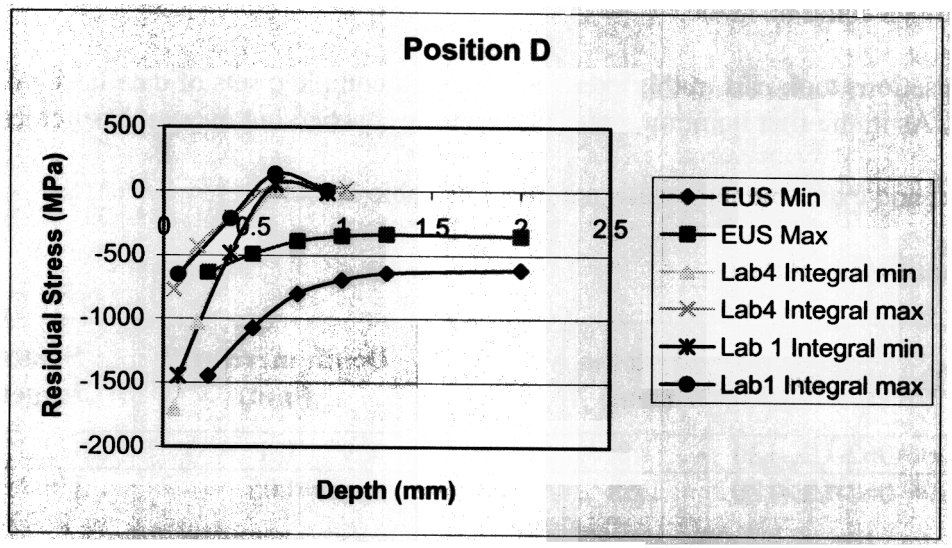


Figure 25 – Stress data for position D on shot-peened steel

Figure 25 is not a very good representation of the expected stress distribution and this is caused mainly by the large differences in the strain readings. The data obtained at Position E has the best quality strain data and this is generally reflected in the stress distribution presented in Fig 26, further highlighting the importance of good quality strain data and the importance of accurate and meticulous measurement practice.

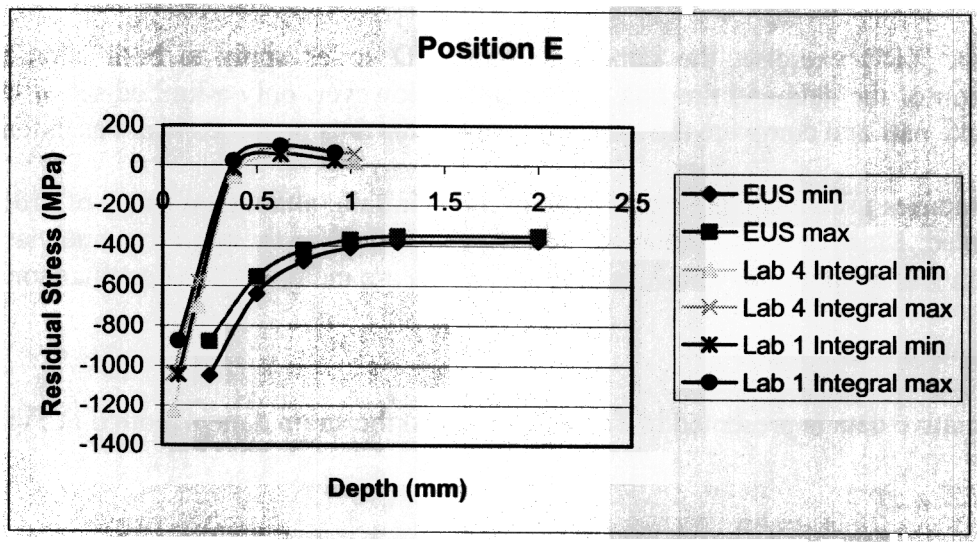


Figure 26 – Stress data for position E on shot-peened steel

5.3 Second Iteration

To try and reduce the uncertainty and scatter in the hole drilling data, a repeat exercise was carried out on the shot peened steel specimens previously used in the XRD exercise. In this case, surface preparation of each block was carried out at NPL to a standard procedure prior to distribution to eliminate the effect of surface preparation on subsequent results. In addition, the hole drilling group also examined an aluminium friction stir weld, supplied by Airbus UK.

Measurements were made at 2 locations on both the shot peened steel and the friction stir weld. The gauge locations and directions were clearly indicated so that direct comparisons of individual strain readings could be made.

Six organisations took part in this exercise, although complete sets of data have only been received from five. As in the first iteration, not all laboratories carried out every measurement.

Equipment and experimental details are given in Table 25 below.

Equipment Details

Lab No.	Gauge type	Drill dia (mm)	No of incre-ments	Depth increment (mm)	Strain logger	Analysis technique
1	CEA-06-062-UL-120	1.8	16	0.1	MG P3500	Integral
2	CEA-06-062-UL-120	1.58	21	0.05	Tinsley 8692	Integral
3	CEA-06-062-UL-120	1.6	9	0.13 then 0.25	MG P3500	Basic/Blind hole
4	CEA-06-062-UL-120	1.2 + 0.6 eccentric	11	0.02 for fine increment study	MG P3500	Integral
5	CEA-06-062-UL-120	1.6	12	0.1	MG P3500	Integral
7	CEA-06-062-UL-120	1.6	22	0.05	MG P3500	No stress data supplied

Table 25: Details of the Hole Drilling equipment used in the second iteration

Unlike the XRD exercise, the same Laboratory ID codes apply to both iterations to simplify comparison of the data and the Lab performance. However, only a limited set of laboratories was able to take part and complete the measurements so the data produced is not as extensive.

All laboratories used the same gauge type in this iteration, although a range of drill and hole sizes were quoted. Most Labs also adopted the Integral method as the preferred analysis technique. No stress data was supplied for Lab 7, but the strain data are included in the comparisons.

Strain data

Representative data is presented in Tables 26-31, and the strain data is plotted in Figs 27 and 28

SHOT PEENED STEEL (POS A)							FRICTION STIR WELD AL (POS C)							FRICTION STIR WELD AL (POS D)						
Z (mm)	SG1 (με)	SG2 (με)	SG3 (με)	Z (mm)	σ_{min} (MPa)	σ_{max} (MPa)	Z (mm)	SG1 (με)	SG2 (με)	SG3 (με)	Z (mm)	σ_{min} (MPa)	σ_{max} (MPa)	Z (mm)	SG1 (με)	SG2 (με)	SG3 (με)	Z (mm)	σ_{min} (MPa)	σ_{max} (MPa)
0.1	50	48	50	0.033	-548	-542	0.1	-22	-3	12	0.033	-25	30	0.1	3	18	25	0.033	-67	-30
0.2	157	171	159	0.15	-612	-600	0.2	-21	8	28	0.15	-28	-7	0.2	20	26	48	0.15	-55	-38
0.3	271	252	258	0.25	-515	-426	0.3	-18	11	42	0.25	-32	-16	0.3	40	58	77	0.25	-52	-40
0.4	316	306	319	0.35	-257	-196	0.4	-9	22	62	0.35	-38	-20	0.4	60	85	103	0.35	-52	-36
0.5	348	343	362	0.45	-125	-63	0.5	1	27	79	0.45	-45	-21	0.5	77	108	126	0.45	-47	-34
0.6	372	366	396	0.55	-73	-7	0.6	12	34	95	0.55	-49	-23	0.6	91	128	145	0.55	-43	-32
0.7	384	381	417	0.65	-35	32	0.7	20	36	108	0.65	-53	-22	0.7	104	144	160	0.65	-40	-32
0.8	393	391	438	0.75	-27	45	0.8	29	39	120	0.75	-58	-24	0.8	113	156	171	0.75	-37	-30
0.9	396	395	446	0.85	28	77	0.9	35	39	129	0.85	-60	-25	0.9	121	166	180	0.85	-37	-31
1.0	399	399	453	0.967	-6	38	1.0	42	40	134	0.967	-78	-40	1.0	125	172	186	0.967	-51	-44
1.1	401	402	457				1.1	46	39	140				1.1	128	177	189			
1.2	402	403	461				1.2	49	37	146				1.2	131	181	193			
1.4	404	406	466				1.4	54	34	153				1.4	132	185	196			
1.6	405	407	469				1.6	55	29	158				1.6	132	186	197			
1.8	407	407	471				1.8	56	25	160				1.8	131	185	195			
2.0	408	408	473				2.0	57	22	164				2.0	130	183	194			

Table 26: Lab 1 Example strain and stress data for measurements on the 2 materials (second iteration)

SHOT PEENED STEEL (POS A)							FRICTION STIR WELD AL (POS C)							FRICTION STIR WELD AL (POS D)						
Z (mm)	SG1 (με)	SG2 (με)	SG3 (με)	Z (mm)	σ_{min} (MPa)	σ_{max} (MPa)	Z (mm)	SG1 (με)	SG2 (με)	SG3 (με)	Z (mm)	σ_{min} (MPa)	σ_{max} (MPa)	Z (mm)	SG1 (με)	SG2 (με)	SG3 (με)	Z (mm)	σ_{min} (MPa)	σ_{max} (MPa)
0.050	32	28	35	0.043	-1572	-1489	0.051	1	4	10	0.043	-114	-40	0.051	0	6	18	0.043	-189	-40
0.101	70	62	75				0.102	3	8	18		-41	-36	0.102	0	14	34		-81	-28
0.152	107	100	115	0.126	-875	-884	0.152	7	12	25	0.126			0.152	3	18	42	0.126		
0.203	139	130	144	0.205	-539	-560	0.203	11	16	29	0.205	-25	-34	0.203	4	20	54	0.205	-66	-32
0.254	165	155	169				0.254	15	21	34		-14	-27	0.254	7	27	65		-57	-31
0.304	186	175	190	0.284	-269	-291	0.305	19	23	36	0.284			0.305	10	32	76	0.284		
0.355	204	193	208	0.367	-101	-120	0.356	22	26	40	0.367	-7	-18	0.356	13	38	86	0.367	-50	-27
0.406	216	205	220				0.406	25	27	42				0.406	14	44	94			
0.457	229	219	232	0.457	-47	-60	0.457	27	29	44	0.457	-3	-12	0.457	17	50	102	0.457	-44	-22
0.508	238	228	240				0.508	30	30	45				0.508	18	55	110			
0.558	248	238	250	0.559	-73	-77	0.559	32	31	46	0.559	-2	-11	0.559	20	59	117	0.559	-37	-17
0.609	257	246	257				0.61	34	31	47				0.61	21	63	123			
0.660	263	253	264	0.678	-103	-91	0.66	35	31	48	0.678	-3	-13	0.66	22	67	128	0.678	-28	-11
0.711							0.711	38	31	49				0.787	22	75	138			
0.787	276	265	280	0.834	-59	-39	0.838	41	30	50	0.834	-3	-17	0.914	23	81	145	0.834	-14	0
0.914	285	275	289				0.965	46	27	50				1.041	22	86	151			
1.041	293	278	297				1.092	48	26	50				1.168	21	91	157			
1.168	297	280	301	1.103	-55	-67	1.219	51	26	50	1.103	-3	-16	1.295	19	93	159	1.103	-25	0
1.295	300	283	303				1.346	51	24	50				1.422	16	94	160			
1.422	299	285	304				1.473	52	22	49										

Table 27: Lab 2 – Example strain and stress data for measurements on the 2 materials (second iteration)

SHOT PEENED STEEL (POS A)						FRICTION STIR WELD AL (POS C)						FRICTION STIR WELD AL (POS D)					
Z (mm)	SG1 (με)	SG2 (με)	SG3 (με)	σ_{min} (MPa)	σ_{max} (MPa)	Z (mm)	SG1 (με)	SG2 (με)	SG3 (με)	σ_{min} (MPa)	σ_{max} (MPa)	Z (mm)	SG1 (με)	SG2 (με)	SG3 (με)	σ_{min} (MPa)	σ_{max} (MPa)
0.13	60	46	90			0.13	1	-5	6			0.13	-10	10	34		
0.25	172	123	200			0.25	-14	10	44			0.25	-13	27	58		
0.5	323	217	330			0.5	14	36	44			0.5	-8	59	109		
0.75	372	251	362			0.75	40	56	34			0.75	-7	82	152		
1.0	390	266	367	-526	-396	1.0	24	44	6	-13	7	1.0	-7	98	171	-51	-12
1.25	397	274	373			1.25	33	25	-6			1.25	-10	104	183		
1.5	402	277	362			1.5	36	55	-17			1.5	-10	110	186		
1.75	403	279	364			1.75	38	51	-24			1.75	-12	111	188		
2	405	280	364			2	42	52	-25			2	-13	113	186		

Table 28: Lab 3 – Example strain and stress data for measurements on the 2 materials (second iteration)

SHOT PEENED STEEL (POS A)						
Z (mm)	SG1 (με)	SG2 (με)	SG3 (με)	Z (mm)	σ_{min} (MPa)	σ_{max} (MPa)
0.1	55	58	60	0.033	-787	-741
0.2	122	122	131	0.15	-690	-601
0.3	179	185	190	0.25	-450	-351
0.4	216	223	227	0.35	-152	-137
0.5	238	247	250	0.45	-22	-4
0.6	252	263	267	0.55	-2	22
0.7	260	274	278	0.658	31	66
0.8	267	282	286	0.75	-1	1
1.0	275	292	296	0.933	26	35
1.2	280	297	301			
1.4	282	299	304			
1.6	283	301	305			

Table 29: Lab 5 - Example strain and stress data for measurements on one (1 position – second iteration)

SHOT PEENED STEEL (POS A)							FRICTION STIR WELD AL (POS C)							FRICTION STIR WELD AL (POS D)						
Z (mm)	SG1 (με)	SG2 (με)	SG3 (με)	Z (mm)	σ_{min} (MPa)	σ_{max} (MPa)	Z (mm)	SG1 (με)	SG2 (με)	SG3 (με)	Z (mm)	σ_{min} (MPa)	σ_{max} (MPa)	Z (mm)	SG1 (με)	SG2 (με)	SG3 (με)	Z (mm)	σ_{min} (MPa)	σ_{max} (MPa)
0.02	9	8	6	0.008	-883	-712	0.016	-10	-2	2	0.008	-37	236	0.016	-13	-3	2	0.008	-13	299
0.03	21	20	17	0.024	-1002	-883	0.032	-17	0	8	0.024	-107	132	0.032	-21	0	5	0.024	-65	188
0.05	36	32	29	0.040	-1076	-991	0.048	-19	2	15	0.040	-139	23	0.048	-23	4	9	0.040	-98	42
0.06	47	46	41	0.056	-952	-846	0.064	-19	4	20	0.056	-133	-22	0.064	-22	6	14	0.056	-100	-32
0.08	60	59	54	0.072	-983	-867	0.08	-19	4	26	0.072	-125	-24	0.08	-23	8	18	0.072	-95	-42
0.10	72	73	68	0.088	-958	-827	0.096	-18	4	28	0.088	-91	-12	0.096	-22	11	22	0.088	-70	-46
0.11	84	87	80	0.104	-844	-705	0.112	-18	4	31	0.104	-49	-5	0.112	-21	13	25	0.104	-67	-50
0.13	96	100	94	0.120	-844	-753	0.128	-18	4	32	0.120	-29	0	0.128	-20	16	29	0.120	-71	-52
0.16	125	128	120	0.144	-772	-711	0.16	-15	5	33	0.144	-40	5	0.16	-19	20	36	0.144	-53	-32
0.19	151	156	149	0.176	-784	-711	0.192	-14	7	36	0.176	-24	-10	0.192	-18	26	42	0.176	-55	-27
0.26	199	208	200	0.223	-534	-475	0.255	-10	8	40	0.223	-29	1	0.255	-15	35	56	0.223	-47	-30
0.13	96	100	94	0.060	-920	-853	0.13	-18	4	32	0.060	-72	28	0.13	-20	16	29	0.060	-68	38
0.25	199	208	200	0.190	-605	-581	0.25	-10	8	40	0.190	-29	-3	0.25	-15	35	56	0.190	-48	-28
0.38	254	268	257	0.380	-102	-84	0.38	2	13	49	0.380	-31	-8	0.38	-10	54	82	0.380	-39	-21
0.51	283	298	287	0.640	16	47	0.51	11	16	56	0.640	-30	-9	0.51	-6	72	104	0.640	-27	-5
0.64	303	317	306	1.020	11	31	0.64	21	18	63	1.020	-47	-12	0.64	-4	86	122	1.020	-14	6
0.76	318	331	320				0.76	28	18	68				0.76	-5	96	136			
0.89	326	336	327				0.89	34	18	72				0.89	-6	103	145			
1.02	333	339	332				1.02	39	16	76				1.02	-9	108	152			
1.14	337	344	336				1.14	43	15	79				1.14	-10	111	157			
1.27	339	346	339				1.27	45	13	82				1.27	-12	113	160			
1.4	341	349	341				1.4	47	11	84				1.4	-14	115	162			

Table 30: Lab 4 - Example strain and stress data for measurements on the 2 materials (second iteration)

FRICTION STIR WELD AL (POS C)							FRICTION STIR WELD AL (POS D)						
Z (mm)	SG1 (με)	SG2 (με)	SG3 (με)	Z (mm)	σ_{min} (MPa)	σ_{max} (MPa)	Z (mm)	SG1 (με)	SG2 (με)	SG3 (με)	Z (mm)	σ_{min} (MPa)	σ_{max} (MPa)
0.05	-1	0	1				0.05	-2	-2	-2			
0.1	-14	-5	4				0.1	-18	-8	3			
0.15	-22	-5	17				0.15	-29	-6	20			
0.2	-24	-3	28				0.2	-43	-7	31			
0.25	-40	-9	16				0.25	-107	-32	33			
0.3	-35	-1	27				0.3	-118	-29	35			
0.35	-30	4	30				0.35	-136	-34	37			
0.4	-33	-1	32				0.4	-138	-24	35			
0.45	-40	-9	25				0.45	-131	-8	54			
0.5	-47	-4	25				0.5	-139	-8	59			
0.55	-46	-5	32				0.55	-130	4	78			
0.6	-32	8	45				0.6	-130	12	86			
0.65	-32	6	49				0.65	-127	20	97			
0.7	-32	6	53				0.7	-143	11	92			
0.75	-39	-14	45				0.75	-133	27	113			
0.8	-30	-10	53				0.8	-133	31	114			
0.85	-37	-19	38				0.85	-134	36	124			
0.9	-31	-15	45				0.9	-136	37	130			
0.95	-30	-11	48				0.95	-146	32	126			
1	-30	-15	50				1	-144	38	134			
1.05	-28	-13	48				1.05	-139	45	138			
1.1	-22	-15	50				1.1	-138	47	143			
1.15	-25	-19	50				1.15	-140	49	143			
1.2	-23	-26	54				1.2	-140	50	147			
1.25	-17	-20	58				1.25	-140	51	150			
1.3	-16	-21	57				1.3	-144	52	150			
1.35	-16	-25	55				1.35	-144	52	150			
1.4	-16	-27	54				1.4	-144	53	150			

Table 31: Lab 7 - Example strain data for measurements on the friction stir weld (second iteration)

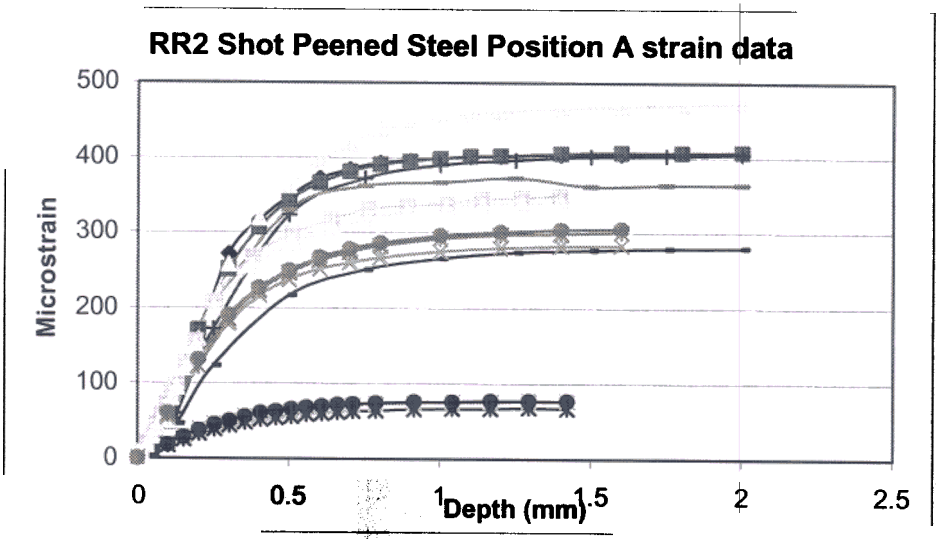


Fig 27: Representative strain profiles for the shot peened steel (2nd iteration)

Generally the scatter in the strain data is considerably reduced compared to that presented in the first iteration (Fig 13), but there was an anomaly with one of the measurements from Lab 2, which has been ignored in the subsequent analysis. The improved performance is almost entirely due to the improved experimental practice, consistent surface preparation and the reduced number of laboratories taking part.

Corresponding data for the friction stir weld (Pos D) are shown below. In this case, the individual strain readings at each location were very different reflecting the highly non-uniform stress gradient across the surface. Position D, which was located at the centre of the weld line, showed the largest strain values, and all the laboratories' results showed increasing strain levels in the order ε1, ε2, ε3, confirming that the same gauge direction had been used by all laboratories.

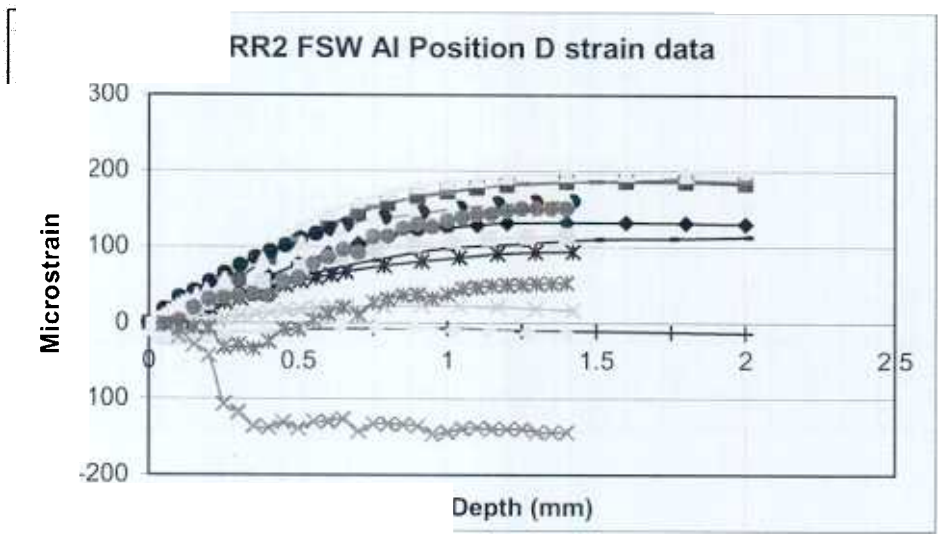


Fig 28: Representative strain profiles for the friction stir weld (Pos D)

Table 32 summarises the strain data in the second iteration.

SHOT PEENED STEEL						
Lab ID	Pos A			Pos B		
	Mean (με)	Range (με)	Range (%)	Mean (με)	Range (με)	Range (%)
1	351	19	5	377	12	3
2	227	13	1	335	12	4
3	290	113	39	252	87	35
4	289	15	5	336	25	7
5	245	12	5	253	46	18

AL FRICTION STIR WELD						
Lab ID	Pos C			Pos D		
	Mean (με)	Range (με)	Range (%)	Mean (με)	Range (με)	Range (%)
1	36	78	216	104	49	47
2	35	15	43	61	92	151
3	31	30	97	53	117	221
4	28	40	143	57	110	193

Table 32: Summary of the 2nd iteration strain data

Generally, for the shot peened steel the scatter in the strain data is much reduced compared with the first iteration (except for Lab 3, which has some problems). The magnitude of the strains is also more consistent.

5.3.3 Stress data

Figures 29-31 show the stress profiles generated in the second iteration for the shot peened steel and the Al friction stir weld. Compared with the data from the first iteration, all but one laboratory used an implementation of the Integral method to determine the stress profile. Lab 4 carried out tests at very fine increments and the data gives a better insight into the profile closer to the surface.

The data for the friction stir weld specimen is reasonably consistent despite the widely varying strain values, but there are inconsistencies with the near surface measurements. Lab 4, which carried out the strain measurements at very fine depth increments, shows a maximum tensile stress of ~ 300 MPa close to the surface which none of the other laboratories can measure. Because of the large degree of scatter in the individual strain gauge readings and the high stress gradients across the surface, the results in Figs 30 and 31 should be treated with caution. Further work is required to validate and verify the measurements on the friction stir weld, but these are outside the scope of the present work.

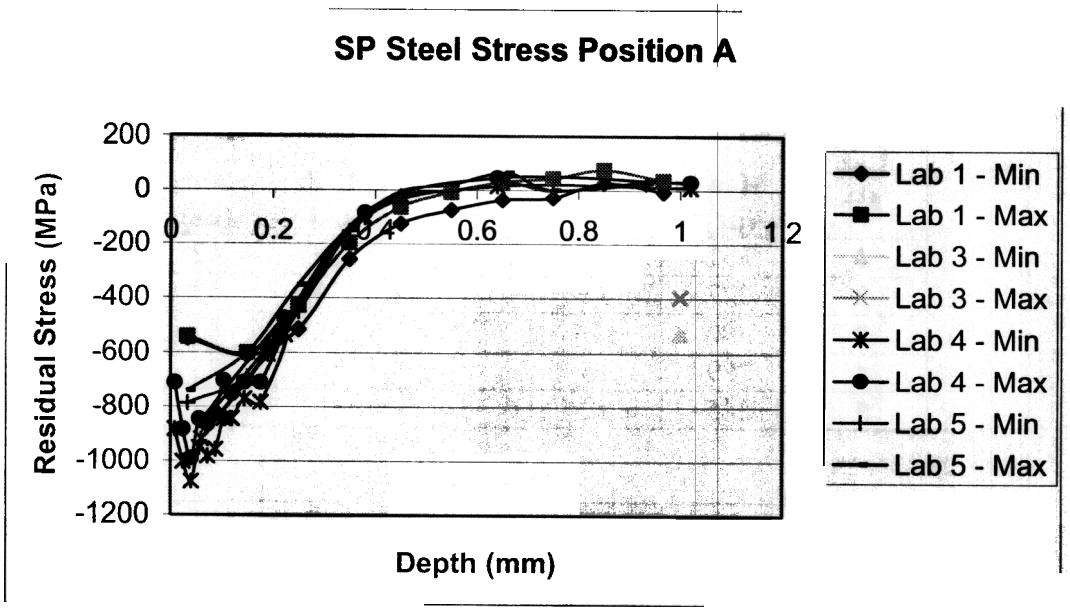


Fig 29: Profile of residual stress vs depth for position A on the shot-peened steel (2nd iteration)

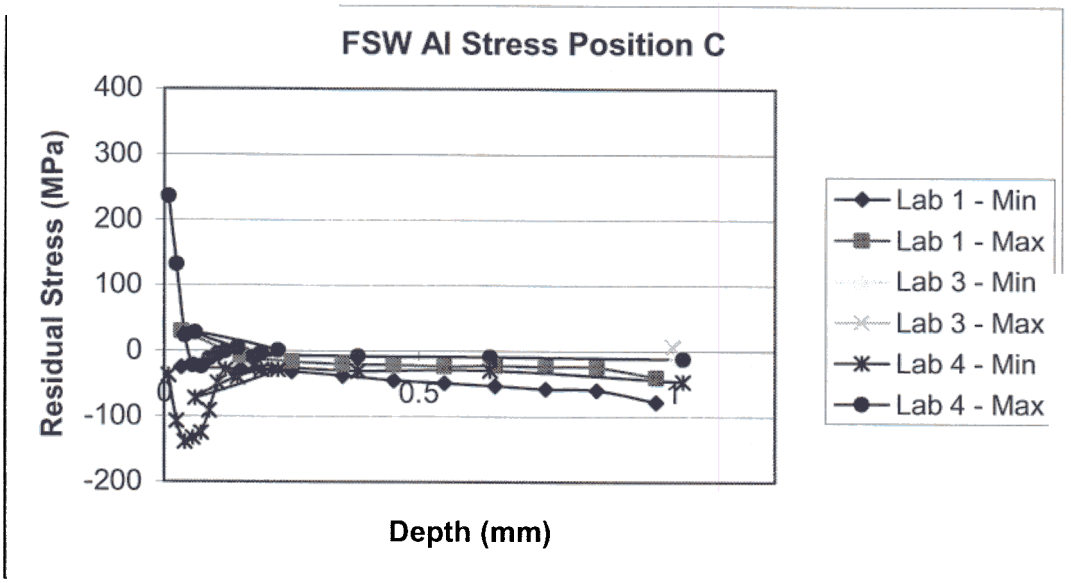


Fig 30: Profile of residual stress vs depth for position C on the Al friction stir weld (2nd iteration)

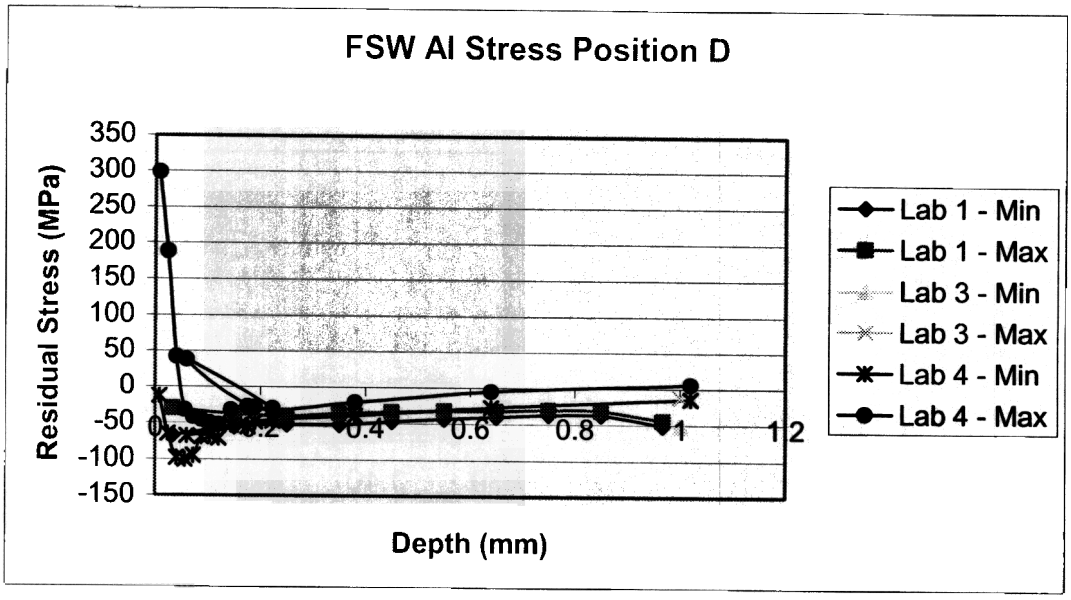


Fig 31: Profile of residual stress vs depth for position D on the Al friction stir weld (2nd iteration)

5.3.4 Measurements at fine depth increments

In the second iteration, Lab 4 carried out a series of tests at very fine depth increments to examine the variation of stress close to the surface. The first depth increment was 0.02mm compared with ~0.13mm for most of the other Labs, and implementation of the Integral method gave a first stress value quoted at 0.008mm. Profiles for the shot peened steel and friction stir weld are given in Figs 32 and 33 below.

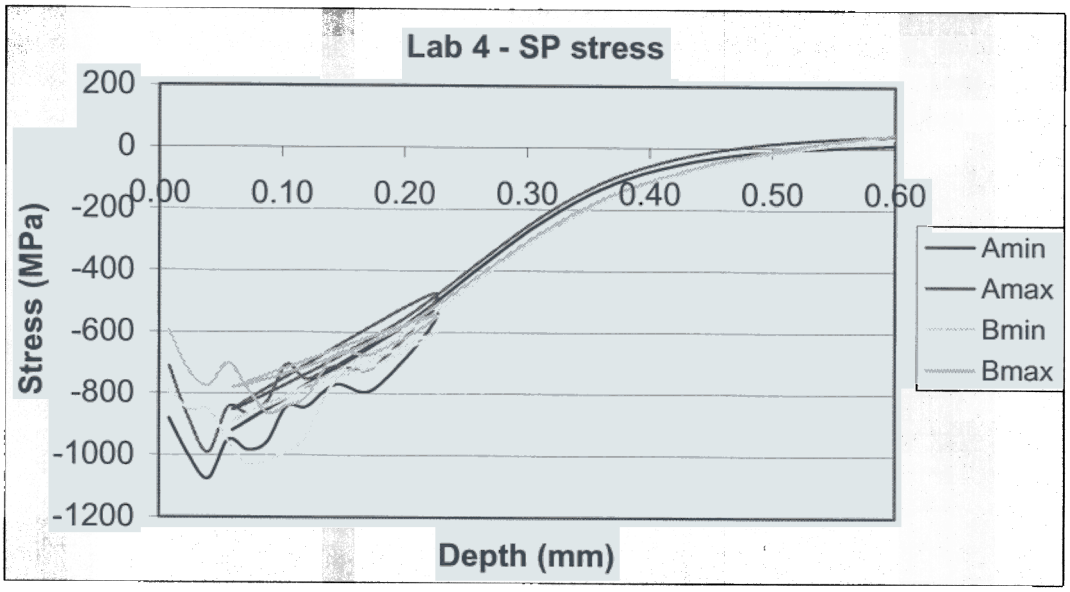


Fig 32: Profile of residual stress vs depth for Lab 4 on the shot-peened steel (2nd iteration) - DATA OBTAINED USING VERY FINE DEPTH INCREMENTS

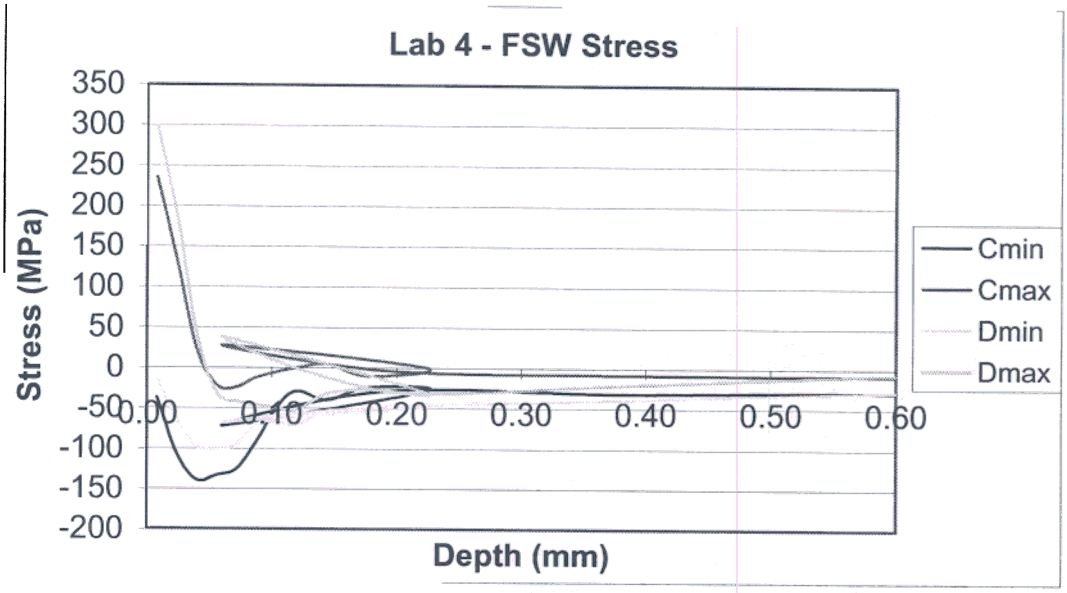


Fig 33: Profile of residual stress vs depth for Lab 4 on the friction stir weld (2nd iteration) - DATA OBTAINED USING VERY FINE DEPTH INCREMENTS

In each case the results from two separate measurements are plotted and the repeatability is excellent. A comparison of the shot peened data shows that the near surface stress is less compressive than was previously thought, with the mean value at –800 MPa.

5.3.5 Comparison of first and second iteration HD results

Table 33 shows a comparison of the **strain gauge data** from the two iterations for the shot peened steel. This was the only material examined in both iterations. Apart from Lab 2, there is greatly reduced scatter in the data for the second iteration and better agreement between the magnitudes of the strains measured. This is almost certainly due to the controlled surface preparation, clearer instructions and improved measurement practice as a result of the experience gained from the first iteration.

SHOT PEENED STEEL						
Lab ID	2nd Iteration (Pos A)			1st Iteration (Pos D)		
	Mean (με)	Range (με)	Range (%)	Mean (με)	Range (με)	Range (%)
1	351	19	5	396	53	13
2	227	13	1	203	95	47
3	290	113	39	176	42	23
4	289	15	5	307	32	10
5	245	12	5	269	297	110
6				235	35	15
7				190	13	7

Table 33: Comparison of shot peened strain data from the two iterations

The results should be examined in conjunction with the corresponding stress profiles in Figs 19 and 29, which confirm the improved performance in the second iteration.

6 COMPARISON OF THE XRD AND HOLE DRILLING DATA

It is difficult to make direct comparisons of the XRD and hole drilling tests because the techniques themselves are very different and the representative volume of material examined is also significantly different. The XRD is essentially a surface technique with typical penetration depths of 5 μm, 15 μm and 50 μm for titanium, steel and Al respectively and depth resolutions of 10-20 μm. In most cases for hole drilling the first depth increment was of the order of 0.1 mm.

In this report, comparison of the hole drilling measurements themselves were made at a nominal depth of 0.5mm, because all Labs reported readings at this point. Only Lab 4 carried out measurements at very fine increments to provide more detailed information in the near surface layers.

General conclusions from the exercise are that the hole drilling results showed greater scatter in the results compared to the XRD, although the values for the as received spring steel and quenched aluminium were not significantly different than the XRD. Qualitatively, the results from the two techniques were in good agreement - of the same magnitude and sign.

The hole drilling results for the shot peened surface tended to over-estimate the compressive stress compared with XRD (~ -800MPa cf –535 MPa for the XRD), but the results from the quenched aluminium were in excellent agreement (~ -170MPa cf –180 MPa for the XRD).

7 SUMMARY AND CONCLUSIONS

The first iteration of the XRD exercise helped to identify some important deficiencies in the measurement procedures of certain laboratories, particularly related to the calibration of equipment and experimental set-up. Results in the second iteration generally showed excellent repeatability amongst the laboratories and reduced measurement uncertainties. For the quenched aluminium sample, the overall scatter in the XRD data was reduced by about 40% (comparing the standard deviations). There were small differences between the values measured in the two iterations, and a small systematic error in the reference values measured at NPL and subsequent measurements by the other laboratories.

In the second iteration, measurements on a 6082 aluminium alloy caused some problems because of the difficulties associated with the texture in the sample. The results show greater scatter between laboratories than seen with the quenched 7010 Al block, but overall the Laboratory repeatability was generally very good (typically ± 1-2MPa for repeat measurements on the 7010 aluminium)

The hole drilling data in the first iteration was variable. Results for the as-received steel and quenched aluminium samples were in reasonable agreement but there were considerable differences and problems with the shot peened steel sample, which had a highly non-uniform stress profile. The main conclusion was that there was potential for at least two laboratories to improve their measurement technique, and the large variation in both the magnitude and scatter in the strains measured by the different participants highlights the scope for improvements in measurement practice. This was largely addressed with the repeat measurements in the second iteration, which showed excellent repeatability and improved quality data. All but one laboratory in the second iteration adopted the Integral method for analysing their data, and this is a key recommendation and finding from this exercise. A further validation exercise on representative data sets confirmed the suitability of different implementations of the Integral method.

For the hole drilling measurements, the accuracy of the strain data in the first few increments has an important effect on the subsequent results, as this is where the strain sensitivity is highest and the strain readings themselves are likely to be small and most susceptible to error. The quality of hole drilling data is often directly related to the skill of the operator and the quality of the measurement set-up. It is vital therefore that meticulous measurement practice and the correct analysis method be used for reliable data. NPL Measurement Good Practice Guide No. 53 [4] addresses some of these issues in more detail.

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ACKNOWLEDGEMENTS

This work was carried out as part of project CPM4.5 on the *Methods of Measuring Residual Stress in Components*, which is part of the CPM programme on *Characterisation and Performance of Materials,* funded by the Engineering Industries Directorate of the UK Department of Trade and Industry.

Special thanks are due to Corus, Airbus UK and Metal Improvement Company for the supply of materials and gauges, all to the participants for making the measurements and contributing to the exercise.