Evaluation of Residual Stress Measurement Uncertainties using X-Ray Diffraction and Hole Drilling via a UK Intercomparison Exercise

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.

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Materials Examined

Two materials were examined in the first iteration – a CCr3 spring steel and a quenched 7010 aluminium alloy. Half of the steel was shot peened giving a total of three stress states. Both materials were examined via XRD and hole drilling. In the second iteration, the same block of shot peened material was passed amongst the participating XRD laboratories, together with a heavily textured 6082 aluminium alloy. The hole drilling laboratories re-evaluated the shot peened steel with the surface preparation carried out at NPL, together with an aluminium friction stir weld.

X-Ray Diffraction Results

First iteration

Twelve organisations participated in the first iteration of the XRD exercise. Six different X-ray machines were used in the exercise. Around half of the participants used position sensitive detectors (PSD), which makes the measurement quicker. In this 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. No specifications were given to the participants as to how to treat the data once it had been collected. Figures 1-3 show the results for all laboratories on the three materials studied.

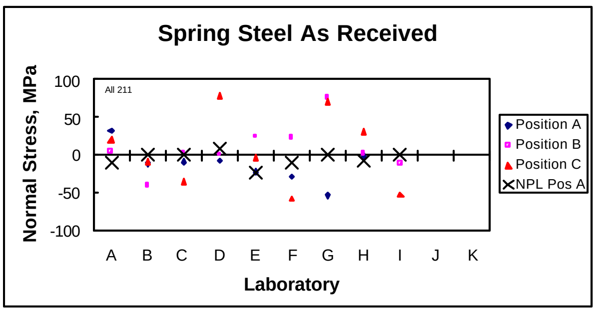

Fig 1: XRD results on the spring steel in the AS RECEIVED condition (1st iteration)

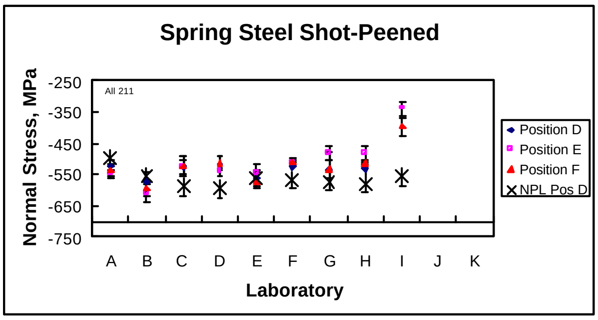

Fig 2: XRD results on the spring steel in the SHOT PEENED condition (1st iteration)

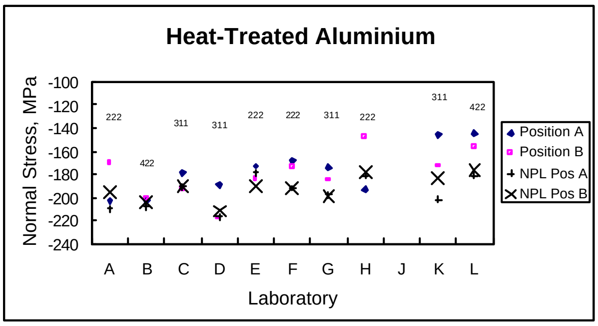

Fig 3: XRD results on the Quenched Aluminium specimen (1st iteration)

This 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.

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. Results are shown in figures 4 and 5.

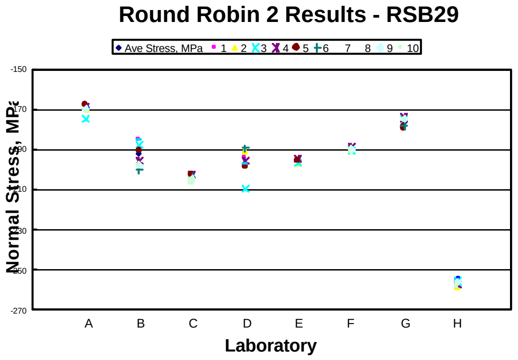

Fig 4: XRD Residual Stress measurements conducted on the same 7010 Al specimen, showing the scatter from repeat measurements and the average value for each Lab

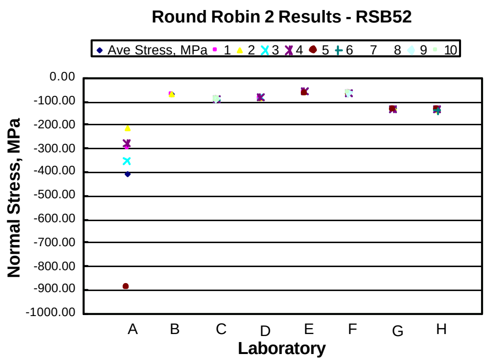

Fig 5: XRD Residual Stress measurements conducted on the 6082 alloy, showing the scatter from repeat measurements and the average value for each laboratory

Results from the second iteration generally show good repeatability with much 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.

Comparison of first and second iteration

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 1: 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 have been used to develop an *NPL Measurement Good Practice Guide on the Measurement of Residual Stresses by X-ray Diffraction* [2].

Hole Drilling Results

First iteration

Eight organisations were involved in the hole drilling study, although not all laboratories carried out every measurement. 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. Stress profiles for the spring steel are presented in figures 6 and 7 for the as-received and shot peened conditions respectively.

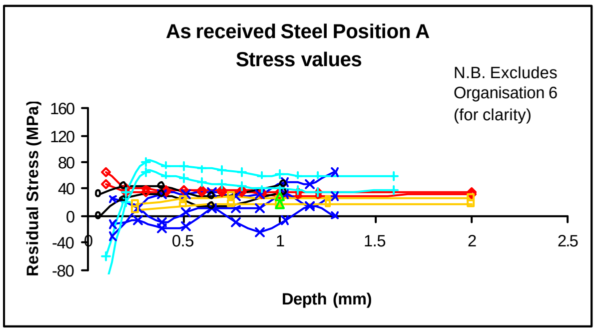

Fig 6: Profile of residual stress vs depth for the as-received steel.

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.

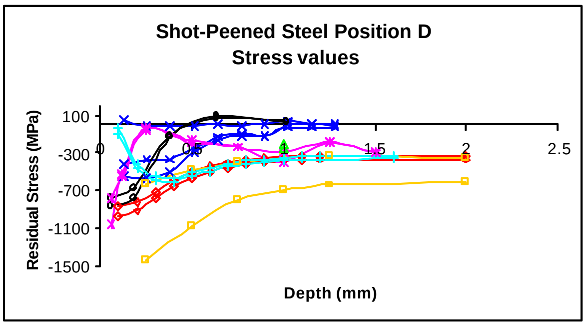

Fig 7: Profile of residual stress vs depth for the shot-peened steel

Figure 7, above, compares the residual stress profiles at position D on the shot-peened steel. Very few labs obtained the expected stress profile. In order to separate out the effect of the different analysis methods used, Figures 8 and 9 show the individual calculated stress profiles grouped according to the EUS (*Equivalent Uniform Stress*) and *integral* analysis methods.

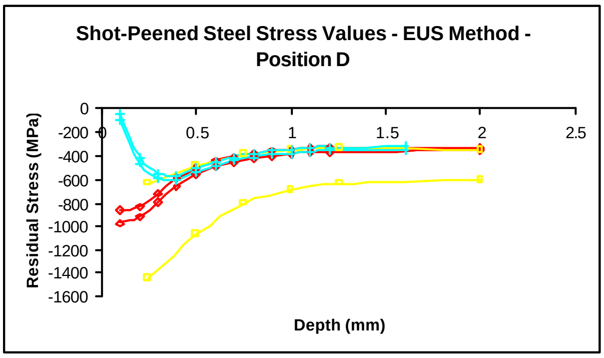

Fig 8: Profile of residual stress vs depth for the shot-peened steel for laboratories that used the EUS method.

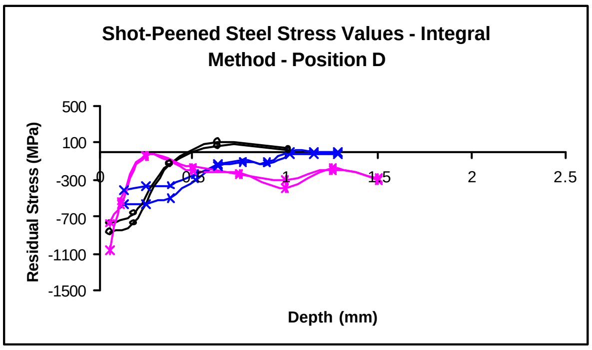

Fig 9: Profile of residual stress vs depth for the shot-peened steel for laboratories that used the integral method.

It is clear that the two analysis techniques produce significantly different stress profiles and there is strong evidence to recommend that for this highly non-uniform stress profile the integral method should be used for analysing the data.

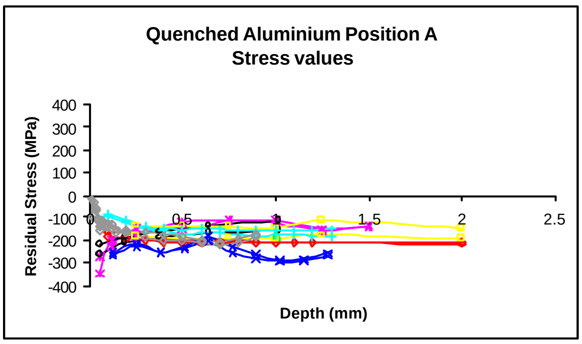

Fig 10: Profile of residual stress vs depth for the heat-treated aluminium

The results for the quenched aluminium, shown in figure 10, show a fairly constant compressive stress over the range of depths, but once again there is some disparity close to the surface – these stresses vary from –100 MPa to –350 MPa.

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, an aluminium friction stir weld was also examined. The gauge locations and directions were clearly indicated so that direct comparisons of individual strain readings could be made.

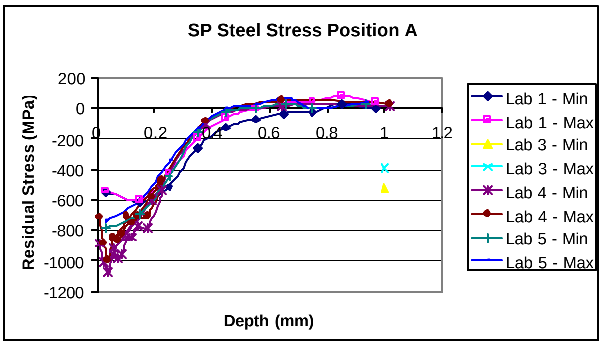

Fig 11: Profile of residual stress vs depth for the shot-peened steel (2nd iteration)

Figure 11 shows the profiles obtained for the shot peened steel in the second iteration. A comparison can be made between Figures 11 and 7. Generally the scatter in the data is considerably reduced compared to that presented in the first iteration. This is due to two factors: firstly, a more closely defined measurement procedure was followed, and secondly, all but one laboratory used an implementation of the Integral method to determine the stress profile.

The data for the friction stir weld specimen (figure 12) is reasonably consistent despite the widely varying strain values, but there are inconsistencies with the near surface measurements.

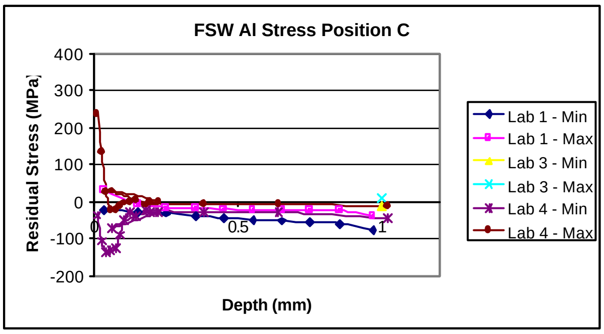

Fig 12: Profile of residual stress vs depth for the Al friction stir weld (2nd iteration)

It is clear, therefore, that hole drilling, when applied with care, can be a repeatable and accurate method of measuring residual stress. However care must be exercised with measurement of depth increments, particularly first depth increments. In addition, it is recommended that the *integral* method be applied to strain data reduction.

Comparison of first and second iteration

Table 2 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						
	2nd Iteration (Pos A)			1st Iteration (Pos D)		
Lab ID	**Mean (µe)**	**Range (µe)**	**Range (%)**	**Mean (µe)**	**Range (µe)**	**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 2: Comparison of shot peened strain data from the two iterations

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.

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).

Uncertainty Evaluation

It is good practice in any measurement to quote the uncertainties associated with the measurement itself. The potential sources of uncertainty for both techniques were identified by the laboratories that participated in the intercomparison exercise. The basic procedure for determining uncertainties can be broken down into a number of steps:

1: Identify the parameters for which the uncertainty is to be estimated
2: Identify all sources of uncertainty in the test
3: Classify all type of uncertainties
4: Estimate the sensitivity coefficient and standard uncertainty for each major source
5: Compute the combined uncertainty
6: Compute the expanded uncertainty
7: Report results

XRD Technique

The sources of uncertainty in the XRD technique have been evaluated through a series of sensitivity tests [1] and the intercomparison exercise previously reported. Details are summarised in Table 3.

Source of uncertainty	Value	Probability Distribution	Divisor d_v	C_i	U_s ±MPa
Repeatability of measurement	±4.1MPa	Normal	1	1	1.3
Modulus of elasticity	±5%	Rectangular	√3	σ	15.8
$Sin^2\psi$ fit	±27MPa	Rectangular	√3	1	15.6
Combined standard uncertainty, u_c		Normal			22.2
Expanded uncertainty ($K u_s$)		Normal (K=2)			44.4

Table 3: Uncertainty evaluation for spring steel

For further information on this uncertainty analysis, refer to the *NPL Good Practice Guide No. 52* [2].

Hole Drilling Technique

Unlike the XRD technique, it is rare to consider in detail the uncertainties associated with the hole drilling technique, as many practitioners believe the method to be more qualitative than quantitative. However, it is possible to make some estimate of the associated uncertainties, an approach which should be encouraged as it can help identify which experimental parameters are likely to give rise to the greatest uncertainty. The main sources of uncertainty in the hole drilling technique have therefore been identified as:

- **Operator skill**

The operator skill has been identified as the most important parameter in achieving a reliable and high quality measurement.

- **Analysis Method**
  Current standards are not appropriate for non-uniform stress fields and other therefore other analysis techniques such as the *Integral Method* need to be used.
- **Measurement Procedure**
  There is a need for accurate depth increment measurements throughout the test, and particular attention must be focused on accurate zero depth detection. In addition, strain gauge installation, drill alignment and temperature compensation are also factors to be considered.
- **Component**
  Parameters such as surface preparation and material geometry have been identified as potential sources of uncertainty.

Summary and Conclusions

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* [3] addresses some of these issues in more detail.

Further Information

Further information is available on other aspects of residual stress measurement including:

[1] Sensitivity Evaluation for X-ray diffraction Residual Stress Measurements, NPL Report MATC(A)104, A Fry. April 2002

[2] M.E. Fitzpatrick, A.T. Fry, P. Holdway, F.A. Kandil, J. Shackleton and L. Suominen: NPL Good Practice Guide No. 52: Determination of Residual Stresses by X-ray Diffraction. March 2002

[3] PV Grant, J D Lord and PS Whitehead: NPL Measurement Good Practice Guide No. 53: The Measurement of Residual Stresses by the Incremental Hole Drilling Technique, May 2002

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Additional Information

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