

**Sensitivity Evaluation
for X-Ray Diffraction
Residual Stress
Measurements**

A Fry

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NPL Materials Centre

ABSTRACT

This report summarises extensive X-ray diffraction residual stress measurements conducted on three different materials, shot-peened spring steel, heat-treated aluminium and a sample of ground titanium. The purpose of the study was to investigate the repeatability of the XRD measurement method and the relative sensitivity of the measurement technique to changes in the test set-up, including the height offset of the specimen, the counting time and the number of Psi tilts used.

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Approved on behalf of the Managing Director, NPL
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1 INTRODUCTION

This report summarises extensive work conducted as part of project CPM 4.5, Measurement of Residual Stress in Components, in which over 250 individual X-ray diffraction tests were conducted to evaluate the sensitivity of XRD residual stress measurements to changes in the test set-up. There are a number of reviews in the literature ^[1] comparing the different techniques, including a review of residual stress measurement methods written as part of the current project ^[2], which can point the reader to further review documents if required. The theory behind the X-ray diffraction techniques and measurement techniques available have been well documented since Bragg first published his law on diffraction, so this study is not intended to address theoretical problems which have already been well addressed ^[3, 4], but rather to examine and evaluate the experimental practicalities of routine XRD stress measurements. The main purpose of this investigation, therefore, is to quantify the uncertainties inherent in XRD measurements of stress and use this information to qualify the scatter in round robin results.

2 SYMBOLS

Symbol	Definition	Units
ARX	The Anisotropy Factor is a measure of the elastic anisotropy of a material. The value of ARX is required for the X-ray Elastic Constants of cubic crystallites calculation by the analysis software. As a guide the following values can be used ^[5] . Cubic, body-centred Fe-base materials: ARX \cong 1.49 Cubic, face centred Fe-base materials: ARX \cong 1.72 Cubic, face centred Cu-base materials: ARX \cong 1.09 Ni-base materials: ARX \cong 1.52 Al-base materials: ARX \cong 1.65	
d	Inter-planar spacing (d-spacing) -the perpendicular distance between adjacent parallel crystallographic planes	Å
d ₀	Strain free inter-planar spacing	Å
d _n	Inter-planar spacing of planes normal to the surface	Å
E	Elastic modulus	GPa
{hkl}	Miller indices describing a family of crystalline planes	
LPA	Lorentz-Polarization-Absorption factor	
S _{1{hkl}} , ½S _{2{hkl}}	X-ray elastic constants of the family of planes {hkl}	MPa ⁻¹
2θ _{φψ}	Peak position in the direction of the measurement	°
φ (phi)	Angle between a fixed direction in the plane of the sample and the projection in that plane of the normal of the diffracting plane	°
ψ (psi)	Angle between the normal of the sample and the normal of the diffracting plane (bisecting the incident and diffracted beams)	°
ε _{φψ}	Strain measured in the direction of measurement defined by the angles phi, psi	
ε ₁ , ε ₂ , ε ₃	Principal strains acting in the principal directions	
σ	Normal stress	MPa
σ ₁ , σ ₂ , σ ₃	Principal stresses acting in the principal directions	MPa
σ _φ	Single stress acting in a chosen direction i.e. at an angle φ to σ ₁	MPa
θ	Angular position of the diffraction lines according to Bragg's Law	°
ν	Poisson's ratio	
1, 2, 3	Principal directions relevant to Cartesian co-ordinate axis	
x, y, z	Directions relevant to Cartesian co-ordinate axis	

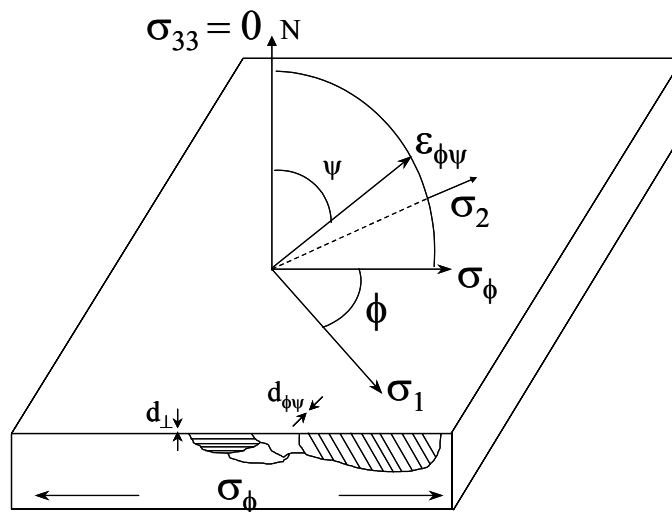


Figure 1 Orientation of strain component ε_{φψ}

3 THEORY AND MEASUREMENT TECHNIQUE

It is useful at this point to introduce briefly the basic theory behind the XRD technique and to describe the analysis method used throughout this report. More detailed explanations can be found in Refs. 3 and 4.

Basically, during an XRD stress measurement the specimen is irradiated with high energy X-rays that penetrate the surface and diffract according to Bragg's law:

$$n\lambda = 2d \sin \theta \quad (1)$$

Where n is an integer, λ is the wavelength of the X-ray, d is the interplanar spacing and θ is the angle of incidence of the X-ray beam.

The detector moves around the specimen and records the angular positions where X-rays have satisfied Bragg's law and diffracted. These peaks form the characteristic spectra for the material. By utilising one of these characteristic peaks, generally at as high a 2θ angle as possible, the strain within a material can be measured by comparing the unstrained inter-planar spacing, d_0 , with the strained inter-planar spacing, d . This can be achieved in several ways, including the two-exposure method, parallel-beam method, $\text{Sin}^2\psi$ method, side-inclination method and a variant of the two-exposure method whereby the inclined measurement is made at $\psi = 60^\circ$ rather than at 45° .

For this investigation the $\text{Sin}^2\psi$ method was used, whereby values of the lattice spacing, d_i , or angular position $2\theta_i$ are plotted against $\text{Sin}^2\psi$, and the stress σ_ϕ is derived from the slope of the line, or elliptical fit using appropriate elastic constants according to the following relationship (see Ref. 3 for full derivation):

$$\frac{d_{\phi\psi} - d_0}{d_0} = \frac{1+\nu}{E} \sigma_\phi \sin^2 \psi - \frac{\nu}{E} (\sigma_{11} + \sigma_{22}) \quad (2)$$

The accuracy with which the peak can be located is fundamental for determining precise strain measurements. This accuracy is dependent on the peak shape, which also depends on how the data was collected. Data collection can be influenced by many factors, for example the step size (between data collection points) and the counting time to name but two.

4 EXPERIMENTAL DETAILS

4.1 XRD MEASUREMENT SYSTEM

X-ray diffraction measurements were performed using a Siemens D500 (Fig. 2), which was set up in Bragg-Brentano geometry with a θ - 2θ drive, with an in-house sample stage (Fig 3) and scintillation detector. The X-ray beam had a collimation of 1° , 1° , 1° and 0.15° for slits I, II, III and IV respectively. The X-ray sources used were a Cr radiation source with a vanadium filter and Cu radiation source with a nickel filter

depending on the material being measured. Experimental details are presented in Table 1.

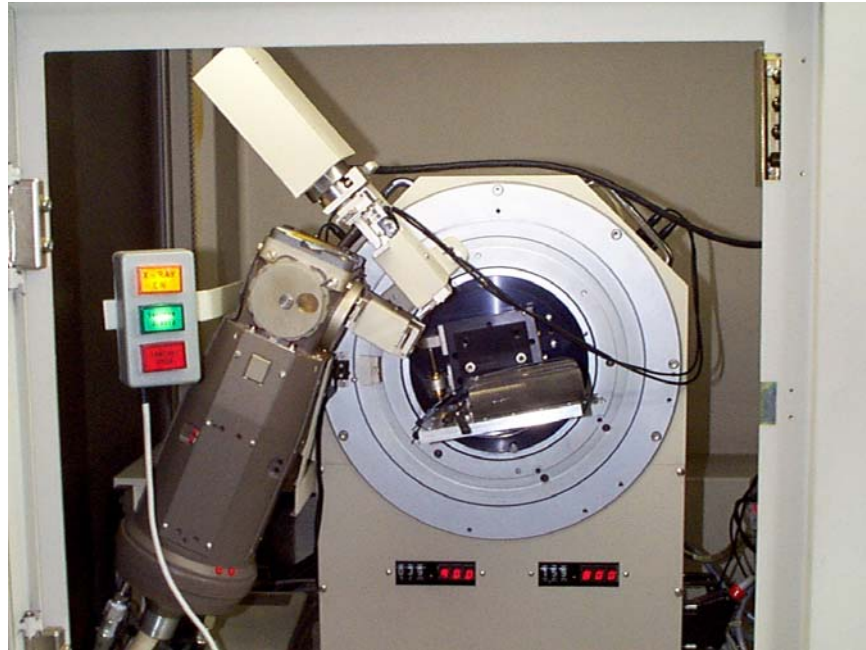


Figure 2 Siemens D500 X-ray diffractometer used for all the residual stress measurements

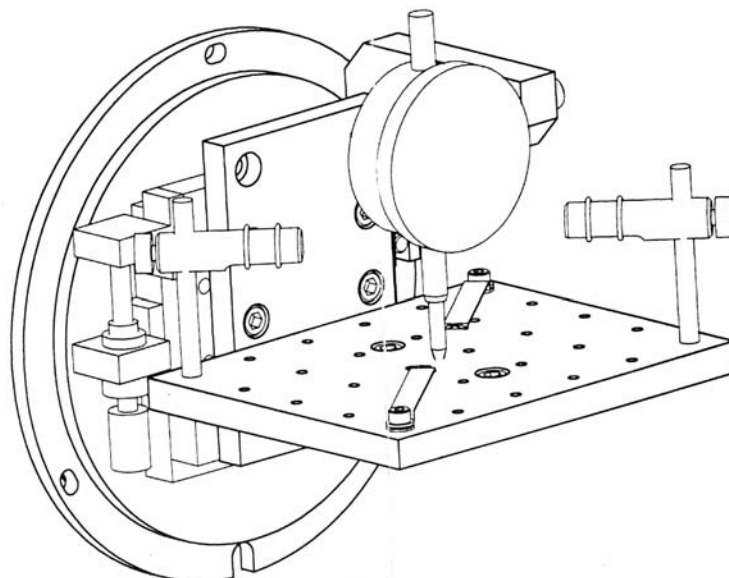


Figure 3 Schematic view of NPL sample stage

The stage was designed so that the height can be altered to accommodate thick or thin specimens. This adjustment can be achieved in two ways, there is a macro adjustment that involves unbolting the stage from the back plate and relocating it using a second set of holes, and a micro adjustment using a fine screw thread. The precise height of the

sample's surface is carefully measured with a dial gauge so that it can be positioned at the centre of rotation of the goniometer.

Table 1 Experimental parameters used for the XRD tests

Material	Anode	Measurement range, 2θ	Step size, 2θ	Count time, s
Spring steel	CrK α	150 – 160°	0.020°	2.0
Aluminium	CrK α	152 – 158°	0.020°	2.0
Titanium	CuK α	136 – 146°	0.020°	5.0

4.2 MEASUREMENT PROCEDURE

The samples were placed on the stage so that the measurement position was at the centre of rotation of the goniometer; this coincides with the position at which the dial gauge measures the sample height. The samples were firmly secured to the stage (Fig. 4), and the height was set with the dial gauge, which was then removed. A 'quick scan' of the sample was conducted over a sufficient 2θ range to locate an appropriate high angle peak on which to perform the residual stress measurement. The $\text{Sin}^2\psi$ technique was used for all the measurements and the resultant peaks analysed using the instrument software package (DIFFRAC^{plus} STRESS, Win-Stress Version 1.04.0726.32). This package supports several different methods of locating the position of the diffracted peak, these are:

- Sliding gravity (thresholds¹ of 10, 20, 30, 40, 50, 60, 70, 80 and average)
- Centre of gravity (30%)
- Parabolic fit (threshold of 80%)
- Pseudo-Voigt fit

All of the raw data had the same systematic corrections applied, these were:

- Absorption correction – eliminates the influence of the irradiated area and the diffraction geometry on the measured intensity distribution.
- Background – eliminates scattered intensity not contributing to the diffraction line.
- Polarisation and Lorentz correction – eliminates the dependence of scattered and diffracted intensity from the diffraction angle theta.
- Smoothing – reduces the effect of counting statistics.
- Alpha 2 – eliminates scattered intensity due to the K α_2 radiation.

The final stress values were calculated by fitting either a straight line or an ellipse through the data points, as appropriate.

¹ The threshold is a peak intensity cut off point, data below which is not used in the fitting procedure, e.g. for parabolic 80%, only the top 20% of the data is used in the peak fitting routine.

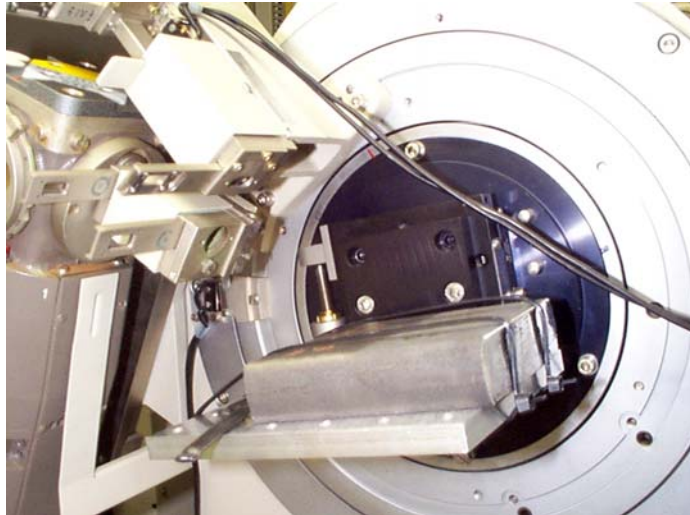


Figure 4 Spring steel block (NPL ID No. RSC30) shown secured to specimen stage

4.3 MATERIALS

Measurements were conducted on three materials a shot peened spring steel block, a heat-treated aluminium block (7010) and a ground piece of titanium alloy. These materials were chosen because they spanned a range of complexities and stress conditions. The data collection details are presented in Table 1.

The above materials exhibited different diffraction characteristics. Initially, measurements were performed on what was considered to be an *easy* sample to measure, the shot-peened spring steel block (supplied by Corus and treated by Metal Improvement Company). One half of the block had been shot-peened (Fig 5) and this gave a single smooth diffracted peak at an angle 2θ for the (211) plane of approximately 155° . This peak was quite broad but was still considered to be an easy peak to analyse. An example of this peak is shown in Figure 6.

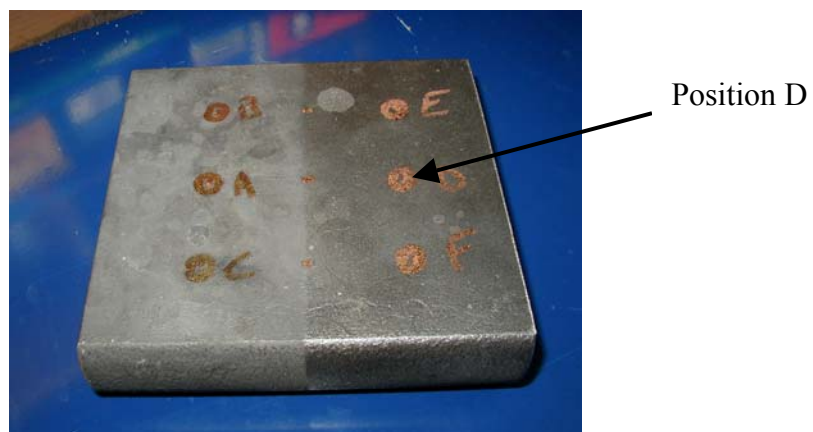


Figure 5 RSC30 – Shot-peened spring steel sample, all measurements were conducted at position D.

All the measurements conducted on the spring steel sample as described within this report were made on the shot-peened half of the block at position D.

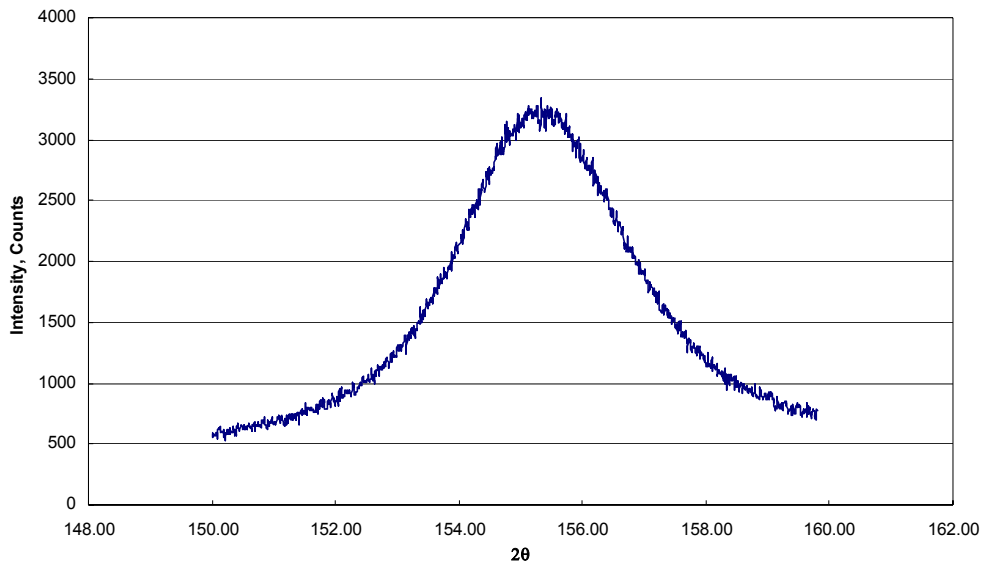


Figure 6 Example of the diffracted peak obtained from measurements at position D on the shot-peened spring steel

The second material examined was a heat-treated aluminium 7010 block as shown in Figure 7 (provided by Airbus). This was considered to be more difficult to measure than the previous steel sample because of a reduction in the count rate and the addition of the $K\alpha_2$ peak (Fig. 7). The diffracting plane used was the (222) plane.

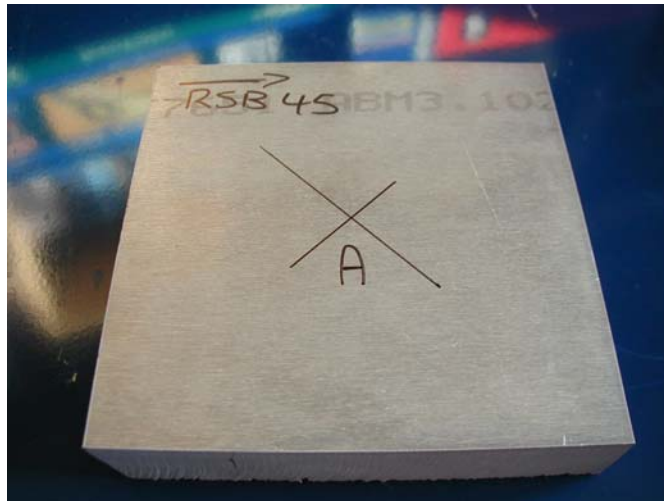


Figure 7 Heat-treated aluminium 7010 sample, all measurements conducted at position A.

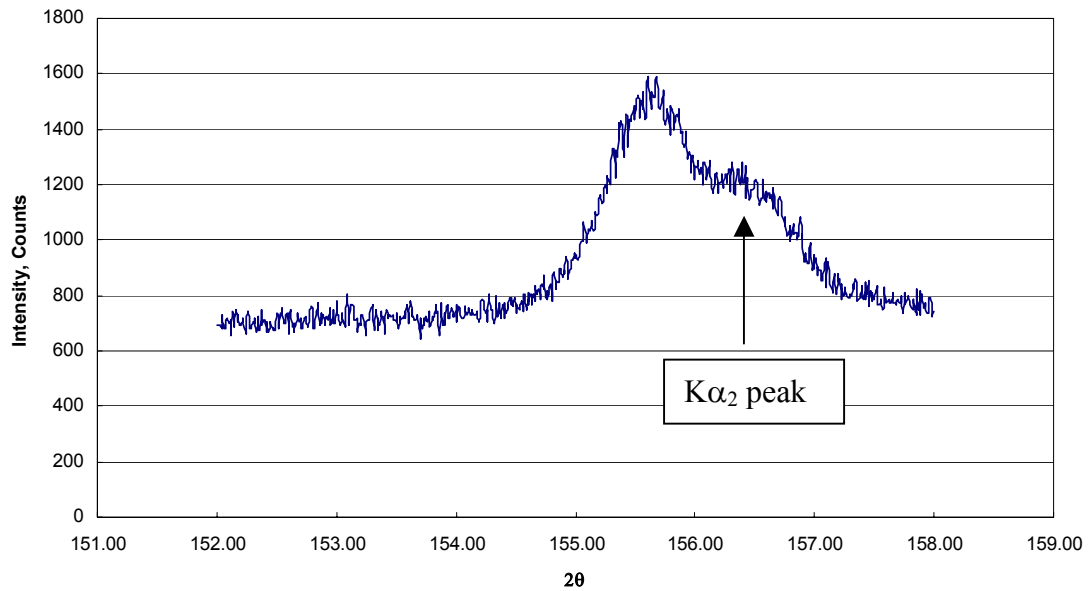


Figure 8 Example of the diffracted peak obtained from the heat-treated aluminium sample

The titanium sample (supplied by QinetiQ) provided a peak that was more problematic to analyse. The count rate was very low and there was more than one peak contributing to the resultant diffracted peak trace. The sample is shown in Figure 9, and an example of the resultant peak is shown in Figure 10.

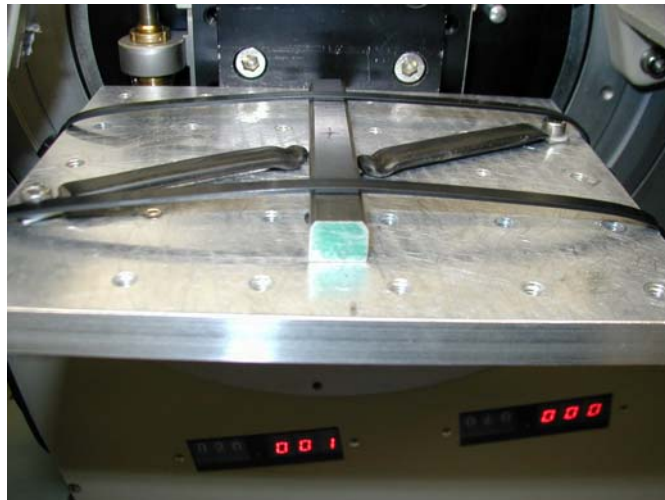


Figure 9 Titanium sample mounted on the specimen stage.

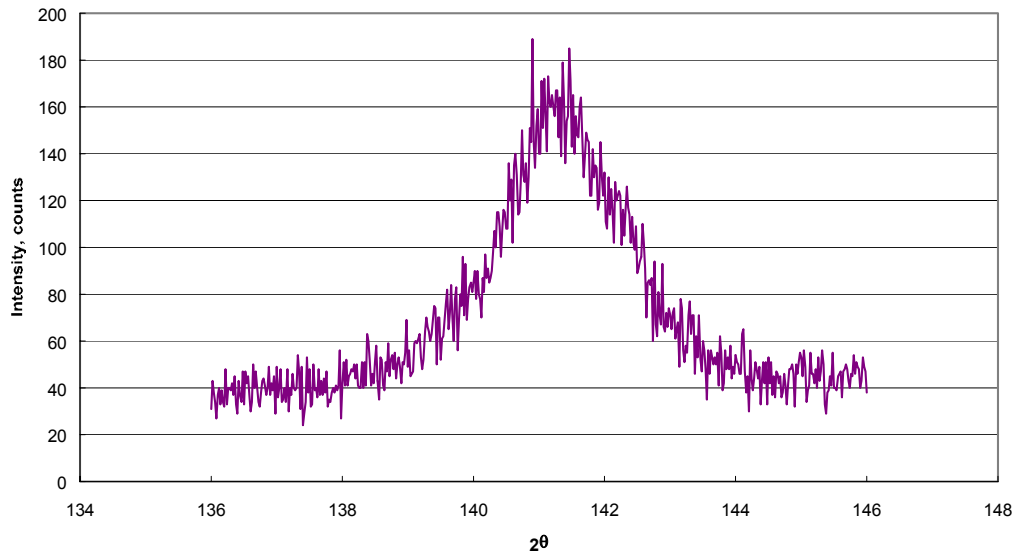


Figure 10 Example of the diffracted peak trace obtained from the titanium sample

5 EXPERIMENTAL DETAILS

The steel, aluminium and titanium samples were all subjected to a similar series of measurements designed to evaluate the relative sensitivity of the measurement technique to changes in the test parameters. The tests were designed to investigate the scatter in the results obtained by introducing deliberate changes in how the test was set-up and conducted. Scatter in the data is a useful measure for quantifying the effect each parameter has on the uncertainties of the measurement, and has been used to establish guidelines for the Good Practice Guide ^[6], which has been produced as part of this project. The tests have been broken down into two regimes, covering the repeatability of the measurement under ideal conditions and the effect of changes in individual experimental parameters.

5.1 REPEATABILITY

To critically assess the effect of changes in the experimental set-up, it is first necessary to establish some measure of the repeatability of the measurements under identical conditions. To establish this, two series of tests were carried out on each material. The first was to establish the repeatability of the equipment and data analysis using the system's software; the second was to establish the repeatability in the testing procedure. Both series of tests are explained in more detail below.

5.1.1 Instrument-Only Repeatability

In these tests, each specimen was placed on the sample stage and secured. The surface was carefully positioned so that it was at the centre of rotation of the goniometer. Ten repeat residual stress measurements were made concurrently under the same conditions. **At no point during these repeat measurements was the sample moved and all the experimental parameters remained unaltered for all ten measurements.**

5.1.2 Instrument-Operator Repeatability

Within this test series, 10 repeat measurements were also made, only in this instance the sample was removed from the machine between each test. Care was taken to ensure that the sample was replaced accurately so that the subsequent measurement was made in the same position as the previous one. **All of the other test parameters remained constant.** This is referred to as “Repeatability 2” within Tables 2-4.

5.2 ADJUSTABLE PARAMETERS

5.2.1 Effect of Height Offsets

A number of tests were carried out where the height of the stage was offset from the centre of rotation of the goniometer. The amount of offset ranged from +1mm to – 1mm. The sample was not removed from the X-ray machine between tests, and all other test parameters remained constant.

5.2.2 Effect of Changes in the Step Size

A series of measurements were made using different detector step sizes. The 2θ step size ranged from 0.01° up to 0.1° in increments of 0.01° . As before, the sample was not removed between tests and all other test parameters were kept constant.

5.2.3 Effect of Changes in the Number of Psi Tilts

Without removing the sample, a succession of residual stress measurements were made using a different number of psi tilts. These ranged from 5 up to 21, but were always split between an equal number of positive and negative values.

5.2.4 Effect of Changes in the Counting Time

The time that the detector counted at each step was also varied; the range was dependant on the material being measured.

5.2.5 Effect of Different Peak fitting Techniques

All the data was analysed using several different methods of peak fitting – necessary to locate the precise peak position. The methods used were governed by those supported by the software package used at NPL, they include: -

- Average sliding gravity
- Sliding gravity at different thresholds
- Parabolic fit
- Centre of gravity
- Pseudo-voigt fit.

6 RESULTS

6.1 SHOT-PEENED SPRING STEEL

The results analysed using the average sliding gravity from all the tests carried out on the shot-peened spring steel have been summarised in Table 2 and Figure 11. The scatter in the results is expressed as the coefficient of variation (CoV), which is calculated by dividing the standard deviation, by the mean value of residual stress. More detailed graphs of all the tests can be found in Appendix A.

Table 2 Average sliding gravity results from the residual stress measurements conducted on the shot-peened spring steel specimen.

Test series	Summary of Residual Stress Measurements, MPa					
	Max	Min	Range	Mean	Standard Deviation	Coefficient of Variation, %
Repeatability	-540	-553	13	-547	4	0.7
Repeatability 2	-537	-563	26	-552	8	1.4
Height	-552	-582	30	-566	10	1.8
Step Size	-551	-568	17	-559	6	1.1
Psi Tilts	-555	-565	10	-559	4	0.7
Count Time	-545	-562	17	-556	5	0.9

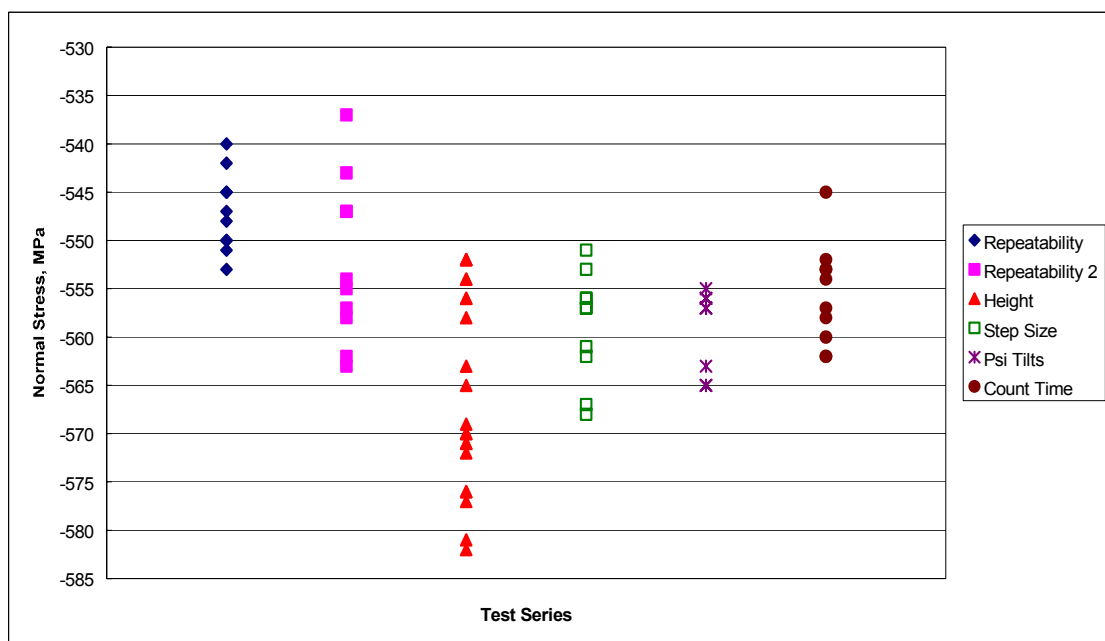


Figure 11 Summary of the XRD residual stress measurements conducted on the shot-peened spring steel specimen

The results showed good repeatability in the measurement. Without removing the sample, the CoV was 0.7%, this increased to 1.4% when the sample was removed and repositioned between successive measurements. The largest spread in measured data within all the tests conducted on the spring steel was in the height sensitivity evaluation, with a CoV of 1.8%.

6.2 HEAT-TREATED ALUMINIUM

An identical series of tests, as carried out on the spring steel, was conducted on the heat-treated aluminium sample. The results of these measurements using the average sliding gravity method are presented in Figure 12 and Table 3; the results are presented in Appendix B.

Table 3 Average sliding gravity results from the residual stress measurements conducted on the heat-treated aluminium specimen.

Test series	Summary of Residual Stress Measurements, MPa					
	Max	Min	Range	Mean	Standard Deviation	Coefficient of Variation, %
Repeatability	-195	-201	6	-198	2	1.0
Repeatability 2	-198	-206	8	-202	3	1.5
Height	-203	-217	14	-212	4	1.9
Step Size	-200	-208	8	-205	3	1.5
Psi Tilts	-203	-209	6	-207	2	1.0
Count Time	-203	-211	8	-206	3	1.5

For this more challenging material, the results showed that there was still very good repeatability in the measurement. Without removing the sample there was a CoV of 1.0% this increased to 1.5% when the sample was removed and repositioned between successive measurements. The largest variation in data within the tests conducted on the aluminium was once again in the height sensitivity evaluation, with a CoV of 1.9%, which is comparable to the spring steel sample.

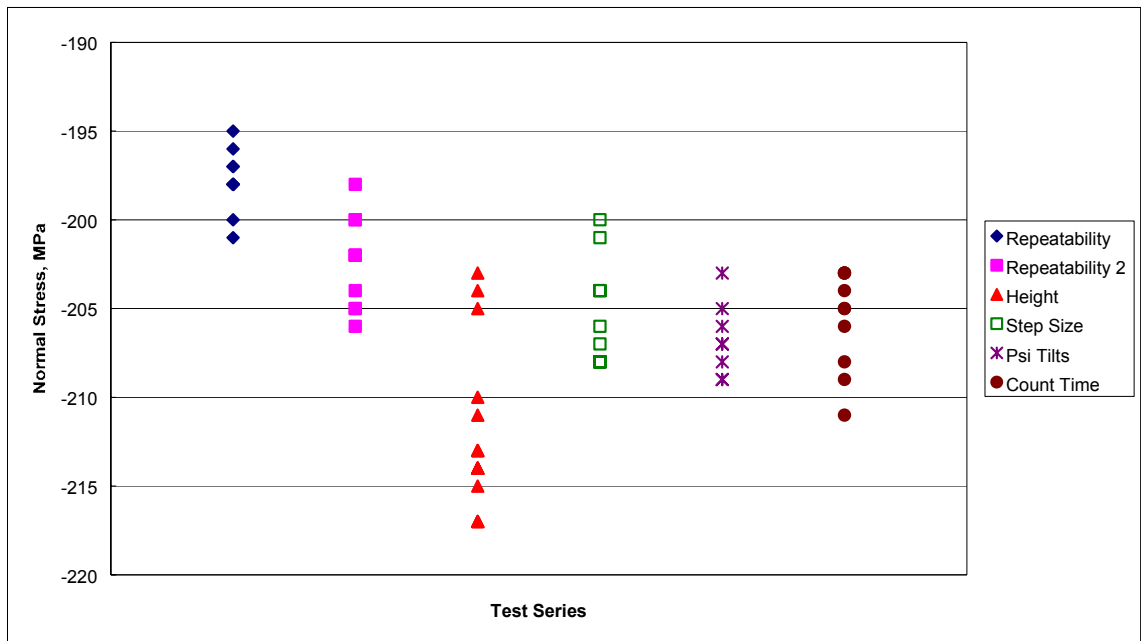


Figure 12 Summary graph of the XRD residual stress measurement conducted on the heat-treated aluminium specimen

6.3 GROUND TITANIUM

Difficulties with the peak shape and counting statistics make the titanium a much more challenging material to perform residual stress measurements on using XRD. A summary graph of all the tests conducted on the titanium is presented in Figure 13. The statistics for each test series are given in Table 4. Full results from the tests are presented in Appendix C.

Table 4 Average sliding gravity results from the residual stress measurements conducted on the ground titanium specimen.

Test series	Summary of Residual Stress Measurements, MPa					
	Max	Min	Range	Mean	Standard Deviation	Coefficient of Variation, %
Repeatability	-403	-440	37	-418	11	2.6
Repeatability 2	-379	-441	62	-410	18	4.4
Height	-403	-440	37	-420	10	2.4
Step Size	-398	-432	34	-418	11	2.6
Psi Tilts	-413	-427	14	-418	5	1.2
Count Time	-375	-466	91	-424	25	5.9

For the titanium the results show that there is still reasonably good repeatability in the measurement. Without removing the sample there was a CoV of 2.6%, which increased to 4.4% when the sample was removed and repositioned between successive measurements. The largest variation observed within these tests was in the count time sensitivity series, with a CoV of 5.9%. This is significantly larger than the variation seen with the steel and aluminium samples.

Generally for all the tests carried out on the ground titanium sample, it was not possible to get a well defined peak for accurate analysis was obtained. This was largely due to insufficient counting statistics. With a longer count time, the author believes that the variation in the results reported for this material could be reduced and be brought more in line with the previous two materials.

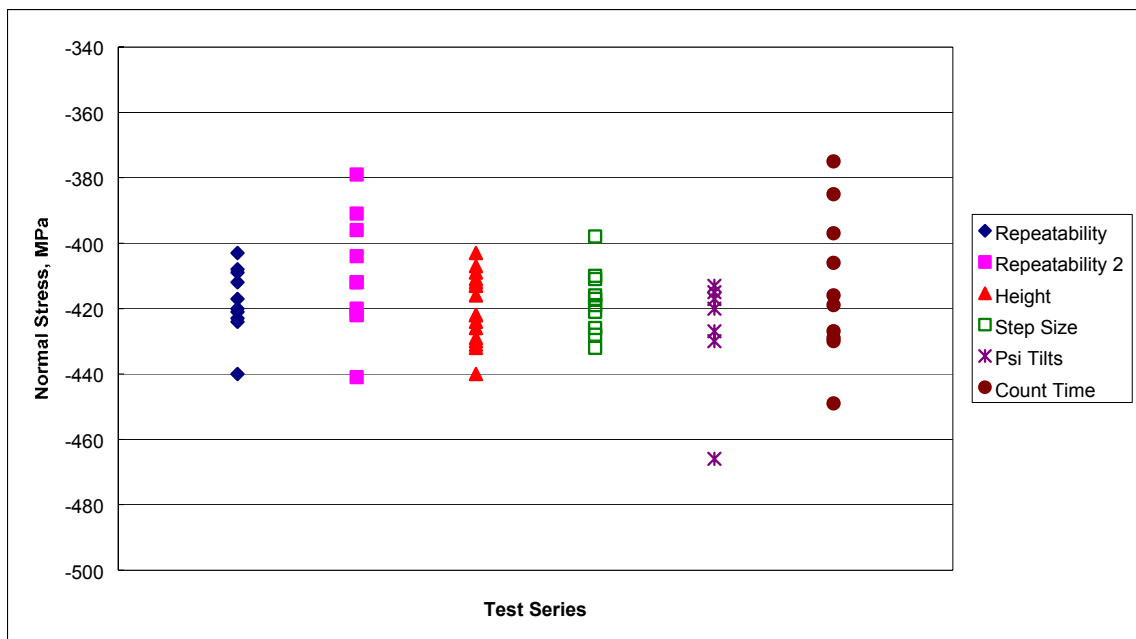


Figure 13 Summary graph of the XRD residual stress measurement conducted on the ground titanium specimen




Table 5 summarises the results for all the tests conducted on the steel, aluminium and titanium samples. Table 6 is a colour-coded table to show the percentage variation in the data for all materials. The tables clearly show that the spread in data is not as great as was initially thought, with the majority being below 5%.

Table 5 Summary of results for the steel, aluminium and titanium samples.

Test Series	Mean Residual Stress, MPa		
	Spring Steel	Aluminium	Titanium
Instrument-Only Repeatability	-547 ± 4	-198 ± 2	-418 ± 11
Instrument-Operator Repeatability	-552 ± 8	-202 ± 3	-410 ± 18
Height	-566 ± 10	-212 ± 4	-420 ± 10
Step Size	-559 ± 6	-205 ± 3	-418 ± 11
Psi Tilts	-559 ± 4	-207 ± 2	-427 ± 5
Count Time	-556 ± 5	-206 ± 3	-413 ± 25

Table 6 colour-coded summaries of results for the steel, aluminium and titanium samples.

Test Series	Coefficient of Variation, %		
	Spring Steel	Aluminium	Titanium
Instrument-Only Repeatability	0.7	1.0	2.6
Instrument-Operator Repeatability	1.4	1.5	4.4
Height	1.8	1.9	2.4
Step Size	1.1	1.5	2.6
Psi Tilts	0.7	1.0	1.2
Count Time	0.9	1.5	5.9

0 – 1.9%  2.0 – 4.9%  >5.0% 

The full numerical results data are presented in Appendix D.

7 PEAK FITTING

The results were analysed using the full range of supported peak fitting routines. There was a high degree of variation in the results obtained. Graphs showing the variation are presented in the Appendices of this report. Tables 7 – 9 show the variation about the mean value of the residual stress for the three materials that were tested. The tables are colour coded as above to allow a quick overview of the influence of different peak fitting routines on the scatter in the data.

For all the materials tested the Pseudo-Voigt fit gave consistently lower scatter. The sliding gravity technique at low thresholds and the average sliding gravity methods also showed reasonable results. In all cases the 80% parabolic fit should be avoided.

Table 7 Variation in the scatter in results depending on the peak fitting routine for the spring steel sample

Test	Coefficient of Variation, %											
	Ave. Sliding Gravity	Sliding Gravity								Centre of Gravity	Parabolic Fit 80%	Pseudo-Voigt Fit
		10%	20%	30%	40%	50%	60%	70%	80%			
Instrument-Only	0.75	0.73	0.70	0.48	0.44	0.83	1.08	1.59	19.37	0.48	4.95	0.67
Instrument-Operator	1.54	1.87	1.38	1.41	1.40	1.36	1.55	1.39	2.08	1.41	4.19	1.60
Height	1.80	2.06	1.71	1.75	1.84	1.76	2.08	23.00	31.50	1.75	4.93	1.87
Step Size	1.00	0.96	0.88	1.28	1.32	1.41	1.65	2.66	21.48	1.28	4.48	0.85
Psi Tilts	0.77	0.87	1.04	1.07	0.81	0.82	1.22	0.88	25.83	1.07	5.12	0.97
Count Time	0.95	1.08	1.01	0.90	0.84	1.20	1.56	2.64	4.26	1.10	10.30	0.82

Table 8 Variation in the scatter in results depending on the peak fitting routine for the aluminium sample

Test	Coefficient of Variation, %											
	Ave. Sliding Gravity	Sliding Gravity								Centre of Gravity	Parabolic Fit 80%	Pseudo-Voigt Fit
		10%	20%	30%	40%	50%	60%	70%	80%			
Instrument-Only	0.89	0.92	1.11	1.07	0.86	0.92	0.97	1.43	2.21	1.04	2.94	0.75
Instrument-Operator	1.28	0.89	1.03	1.30	1.25	1.02	1.21	1.86	14.53	1.30	1.77	1.01
Height	2.06	2.09	2.01	2.09	2.11	2.14	2.25	3.27	3.82	2.09	4.51	2.07
Step Size	1.47	1.52	1.20	0.80	1.19	1.47	2.04	2.42	3.09	0.83	2.37	1.24
Psi Tilts	0.99	1.60	0.81	0.81	0.82	1.21	1.21	1.50	1.89	0.81	4.56	0.93
Count Time	1.36	2.52	2.45	2.02	1.37	1.20	1.62	1.90	1.81	2.02	12.13	1.41

Table 9 Variation in the scatter in results depending on the peak fitting routine for the titanium sample

Test	Coefficient of Variation, %											
	Ave. Sliding Gravity	Sliding Gravity								Centre of Gravity	Parabolic Fit 80%	Pseudo-Voigt Fit
		10%	20%	30%	40%	50%	60%	70%	80%			
Instrument-Only	2.52	2.54	2.03	1.93	2.10	2.59	3.25	4.85	6.65	1.93	11.86	1.15
Instrument-Operator	4.39	2.17	2.51	3.77	4.37	5.12	5.82	7.81	10.31	3.77	17.47	3.11
Height	2.49	1.59	2.33	2.24	2.30	2.62	3.49	5.43	17.91	2.24	26.92	1.53
Step Size	2.52	2.98	3.34	3.07	3.32	3.00	2.42	4.45	5.65	3.07	21.11	1.79
Psi Tilts	1.18	1.76	1.31	1.47	1.32	2.31	2.84	3.23	3.75	1.47	16.97	1.56
Count Time	5.95	5.84	3.55	4.32	4.77	5.55	5.29	7.33	8.95	4.33	69.15	2.77

0 – 1.9% 2.0 – 4.9% >5.0%

8 CONCLUDING REMARKS

Generally all the materials tested showed good repeatability in the measurement for both the instrument-only and instrument-operator repeatability tests. Apart from the count time series of tests on the titanium all the results showed less than 5% variance from the mean value. It is suggested that the poor counting statistics obtained for the titanium sample are the cause for the increase in scatter. It was noted that the repeatability was highly dependent on the peak fitting method used, with the Average Sliding Gravity, Pseudo-Voigt Fit and Sliding Gravity at low thresholds giving the most consistent results with low scatter.

For the materials examined the measurement technique appears to be relatively insensitive to many of the parameters investigated. The greatest sensitivity was found to be with the height setting and the counting time, the latter effect was especially evident with the titanium sample. It should be noted that a height offset in the order of ± 1 mm represent gross misalignment and as such is unlikely in practice. However, the tests do illustrate the relative insensitivity to positioning errors on materials with homogeneous stress states over the surface, such as those used in this study. It is unclear as to the effect with samples that have stress gradients over the surface.

For guidance on Good Measurement practice the reader is referred to the NPL Measurement Good Practice Guide No 52: Determination of Residual Stresses by X-ray Diffraction. March 2002 [Ref. 6].

9 REFERENCES

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- 2 F. A. Kandil, J. D. Lord, A. T. Fry and P. V. Grant, "A Review of Residual Stress Measurement Methods – A Guide to Technique Selection", NPL Report MATC(A)04. February 2001
- 3 I. C. Noyan, J. B. Cohen, "Residual Stress – Measurement by Diffraction and Interpretation", Springer-Verlag, 1987, ISBN 0-387-96378-2
- 4 B. D. Cullity, "Elements of X-Ray Diffraction", Second Edition, Addison-Wesley, 1978, ISBN 0-021-01174-3
- 5 DIFFRAC^{plus} STRESS – Residual Stress Determination, Users Manual, Bruker Analytical X-ray Systems
- 6 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

Acknowledgements

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The authors would like to acknowledge important contributions to this work from Jerry Lord and the XRD Focus Group established for this project.

**APPENDIX A - DETAILED RESULTS FOR SHOT-PEENED
SPRING STEEL**

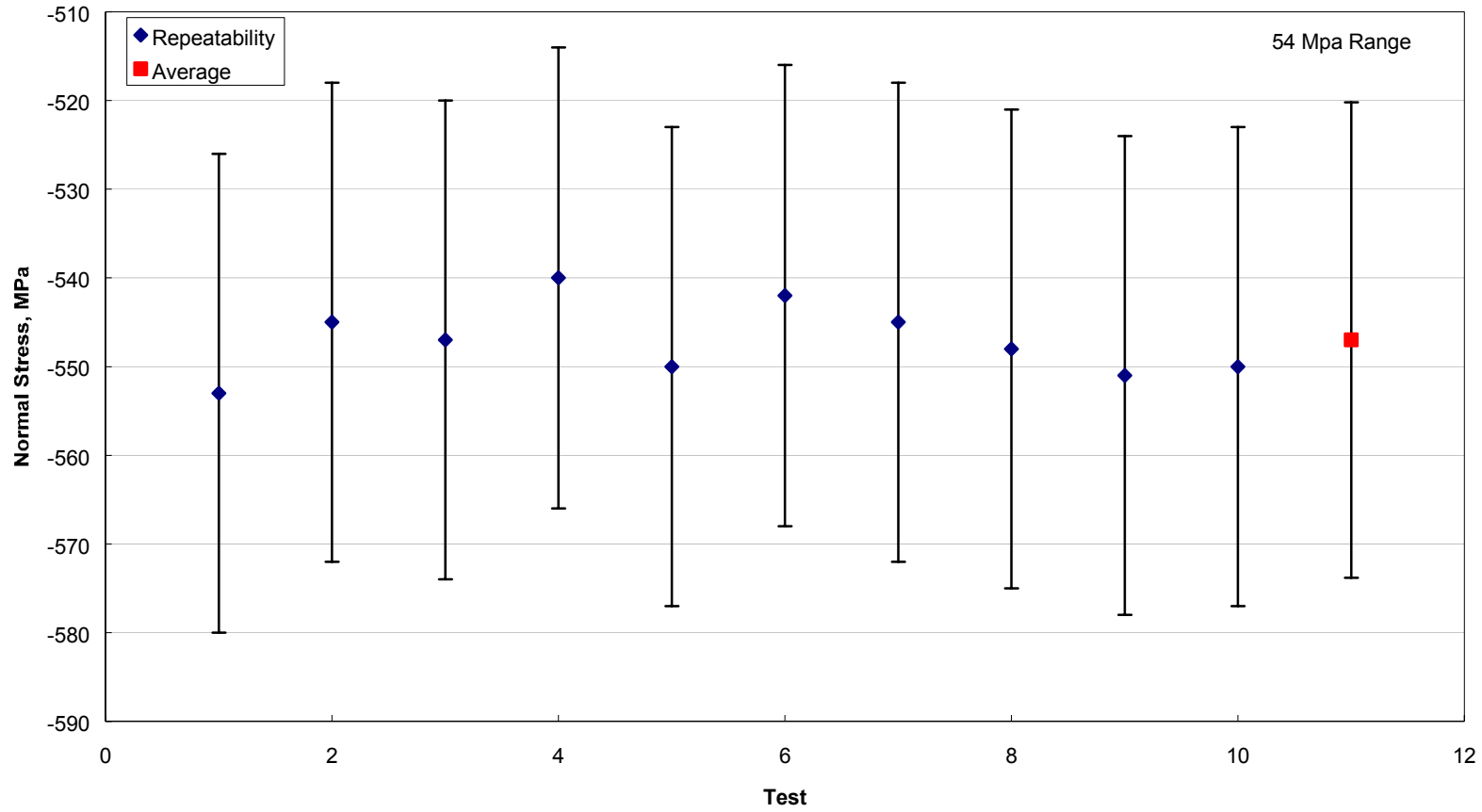


Figure A1 Repeatability of spring steel measurements

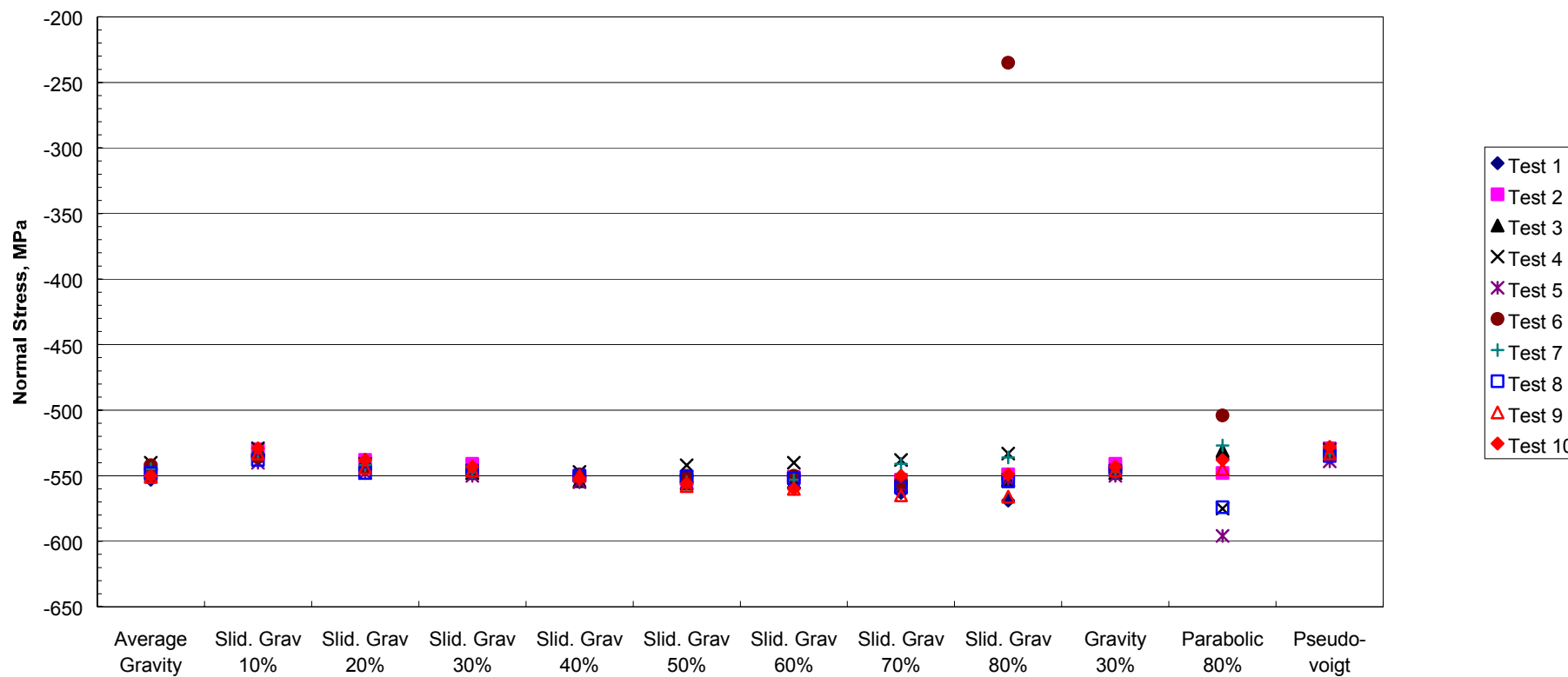


Figure A2 Normal stress distribution for repeatability tests on the spring steel, showing the results for all support peak-fitting routines

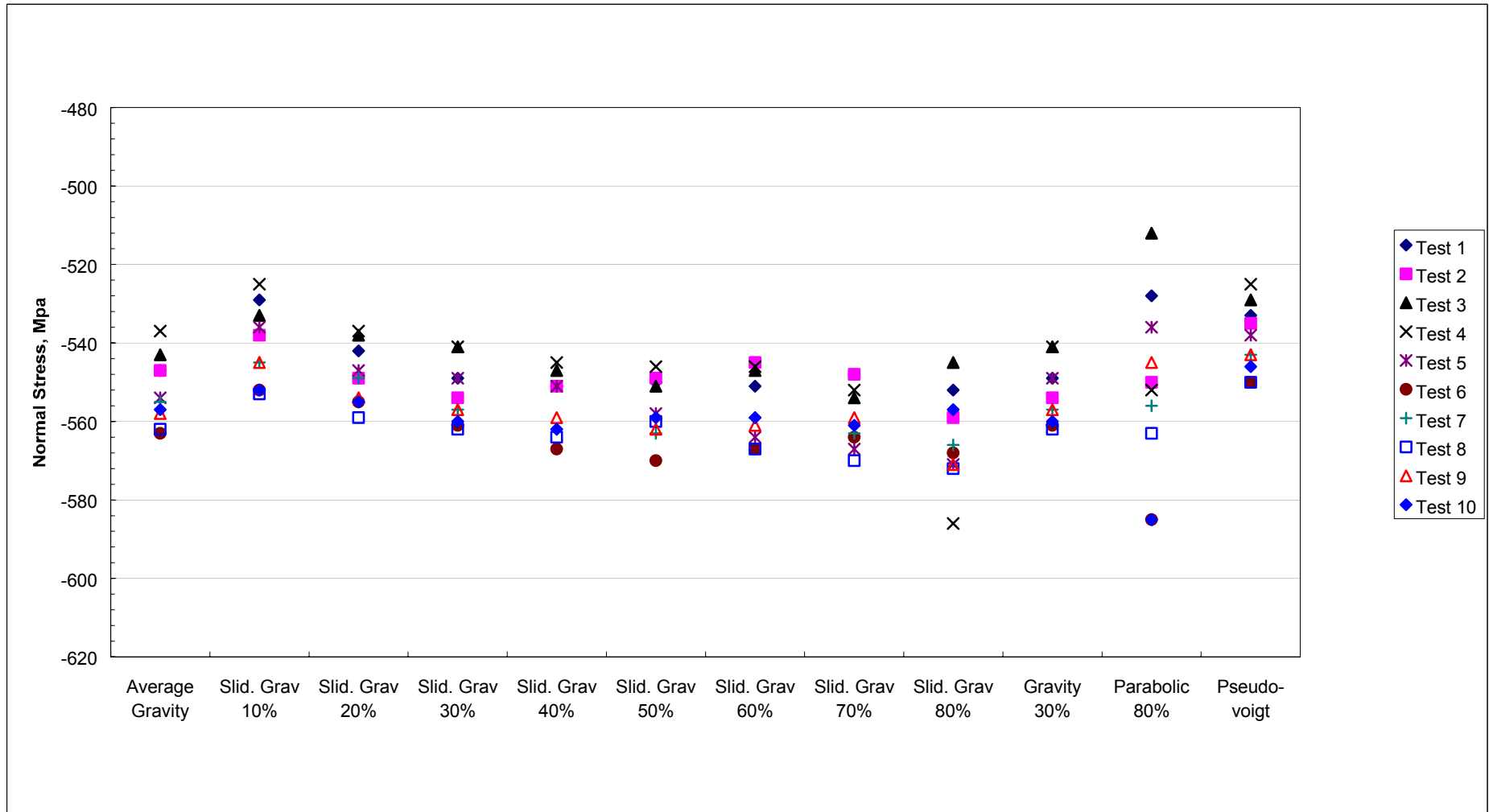


Figure A3 Normal stress distribution for repeatability (removing the specimen between tests) tests on the spring steel

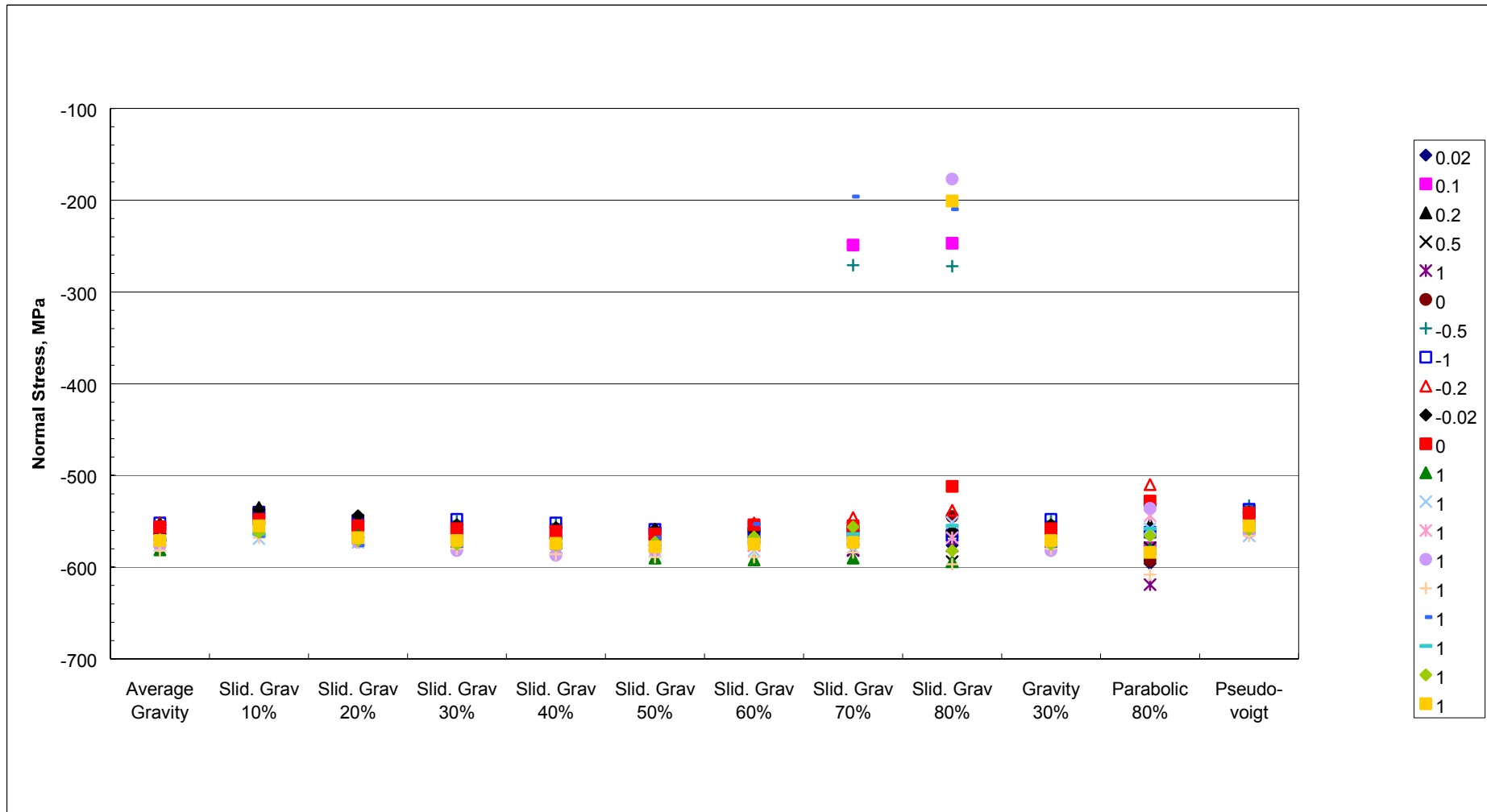
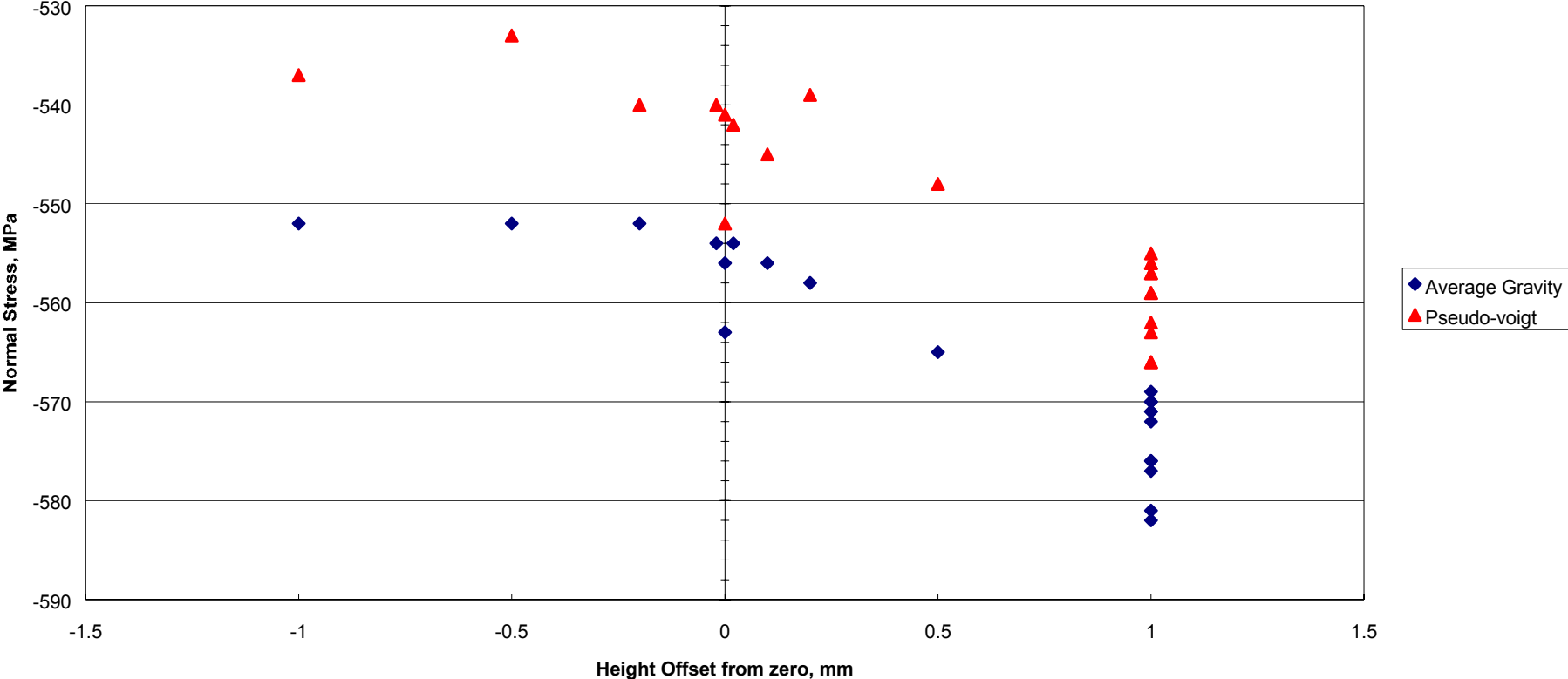


Figure A4 Normal stress distribution for height sensitivity tests on the spring steel



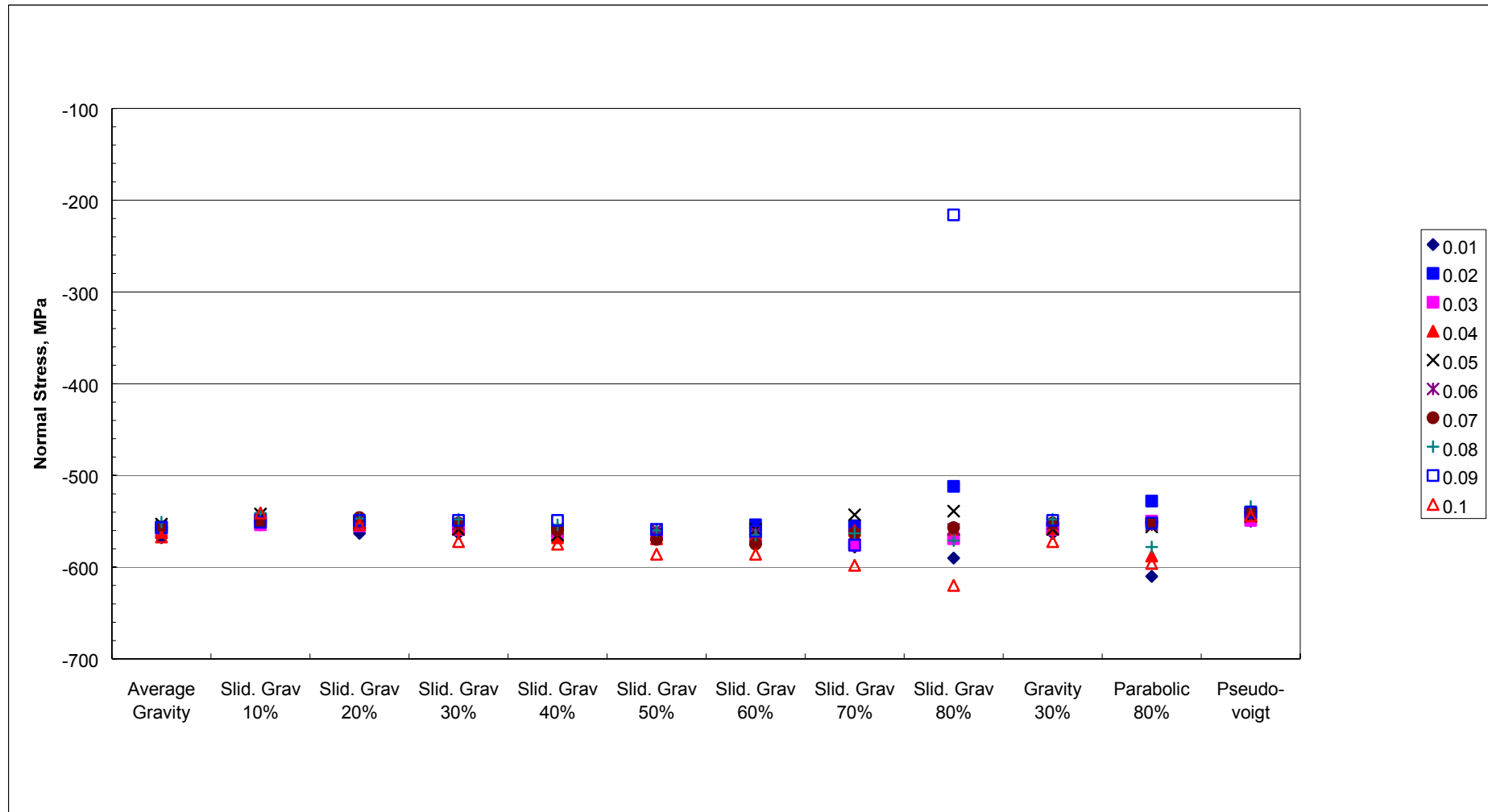


Figure A6 Normal stress distribution for step size sensitivity tests on the spring steel

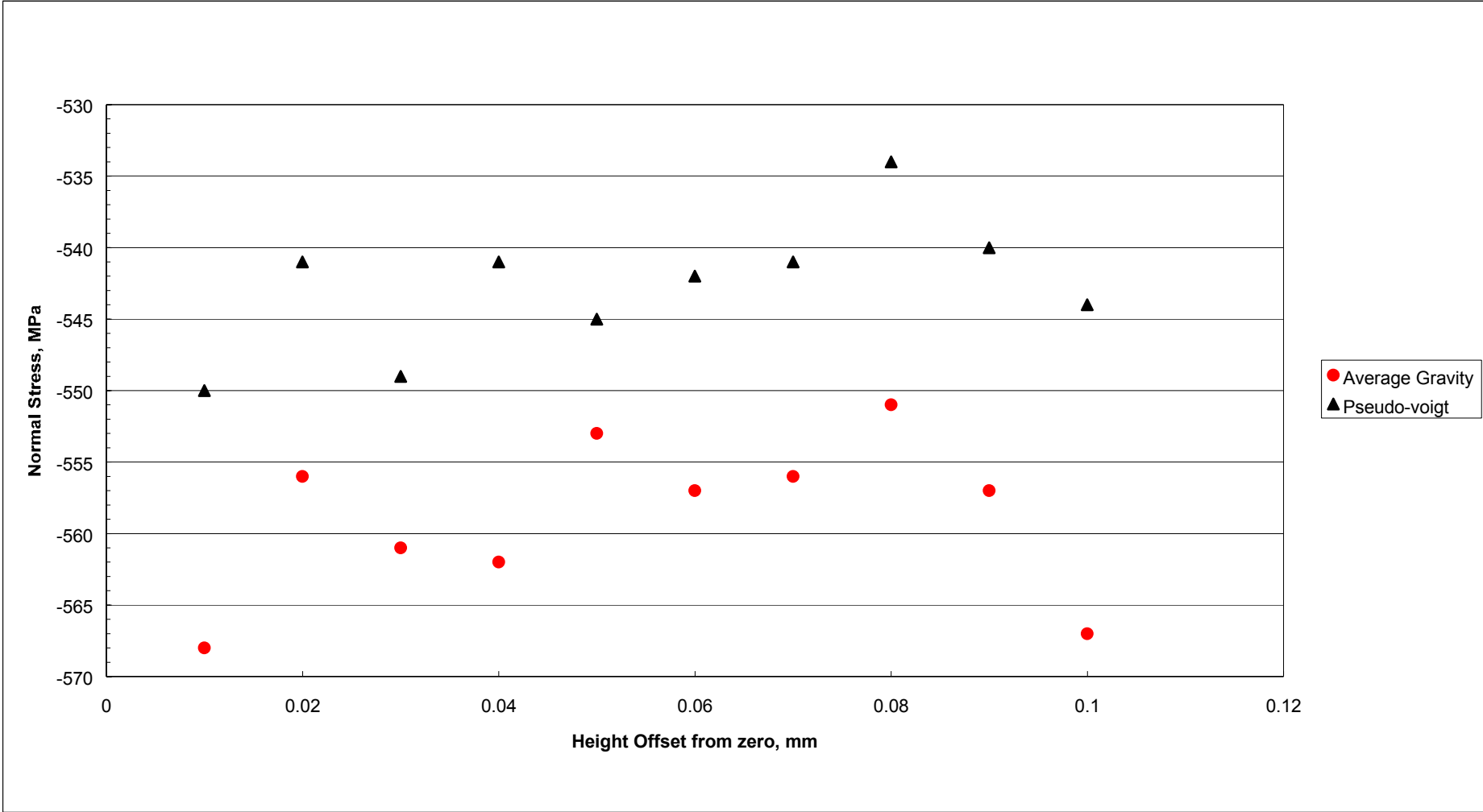


Figure A7 Normal stress distribution for step size sensitivity tests on the spring steel

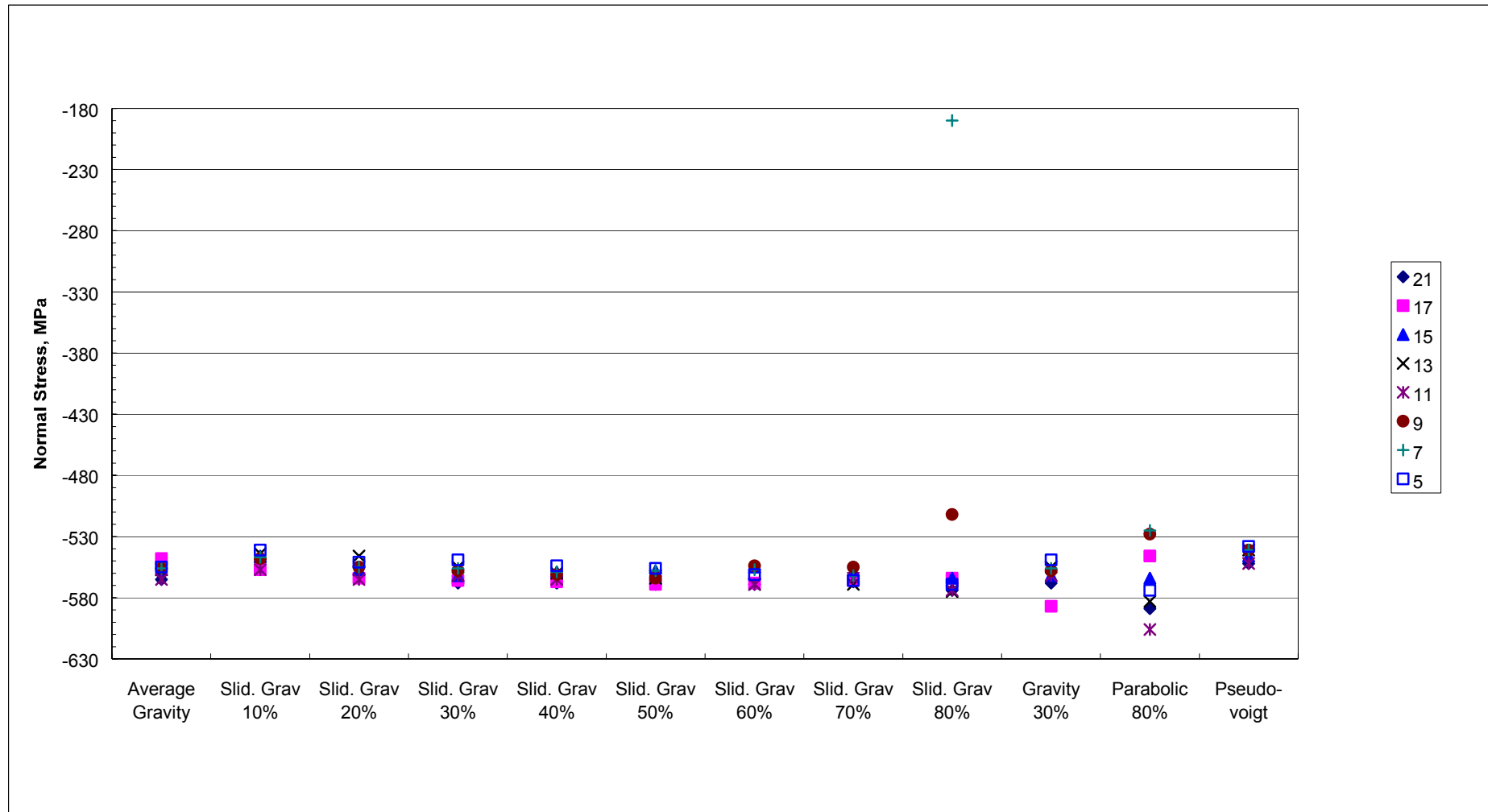


Figure A8 Normal stress distribution for psi tilts sensitivity tests on the spring steel

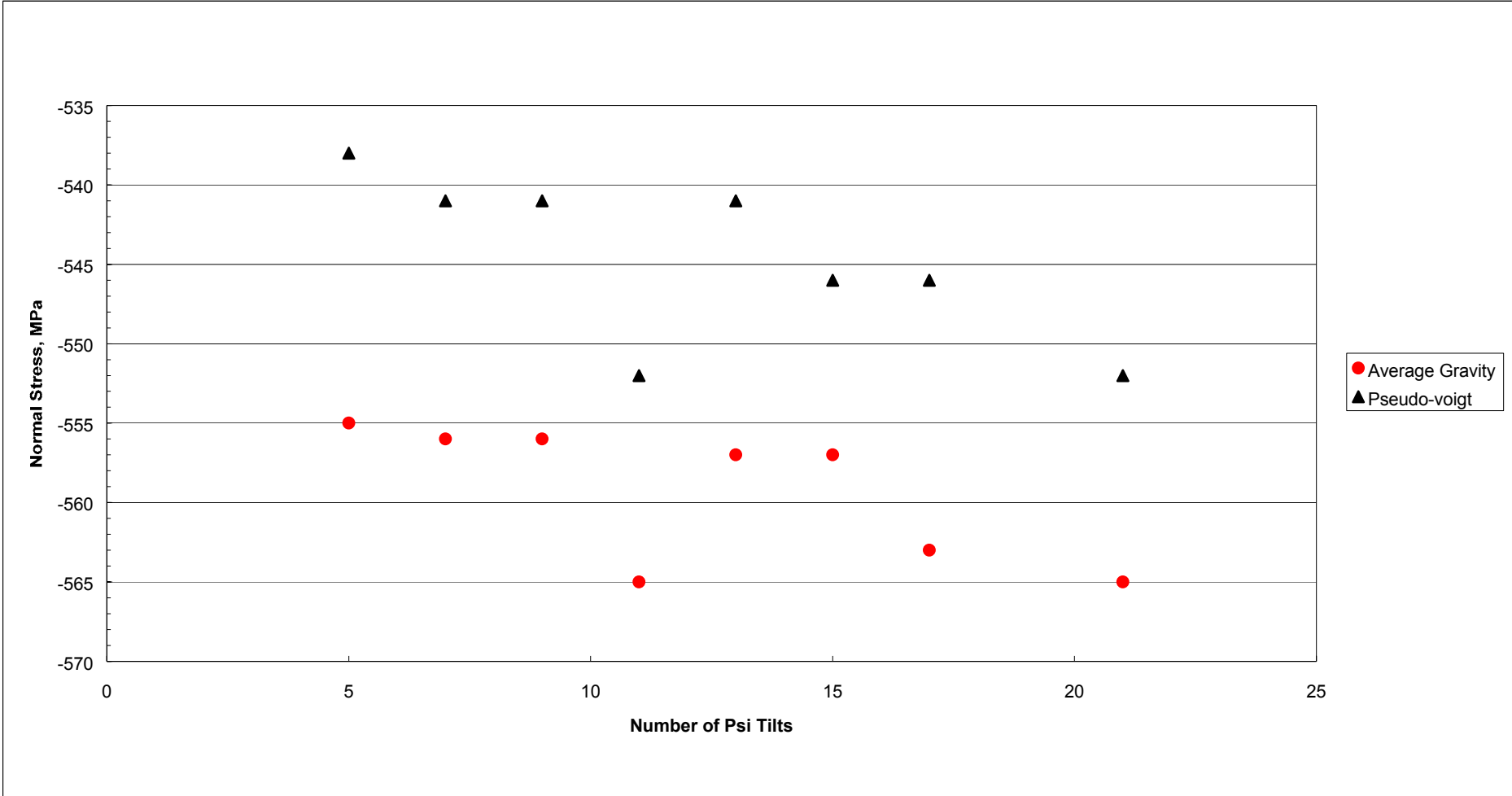


Figure A9 Normal stress distribution for psi tilts sensitivity tests on the spring steel

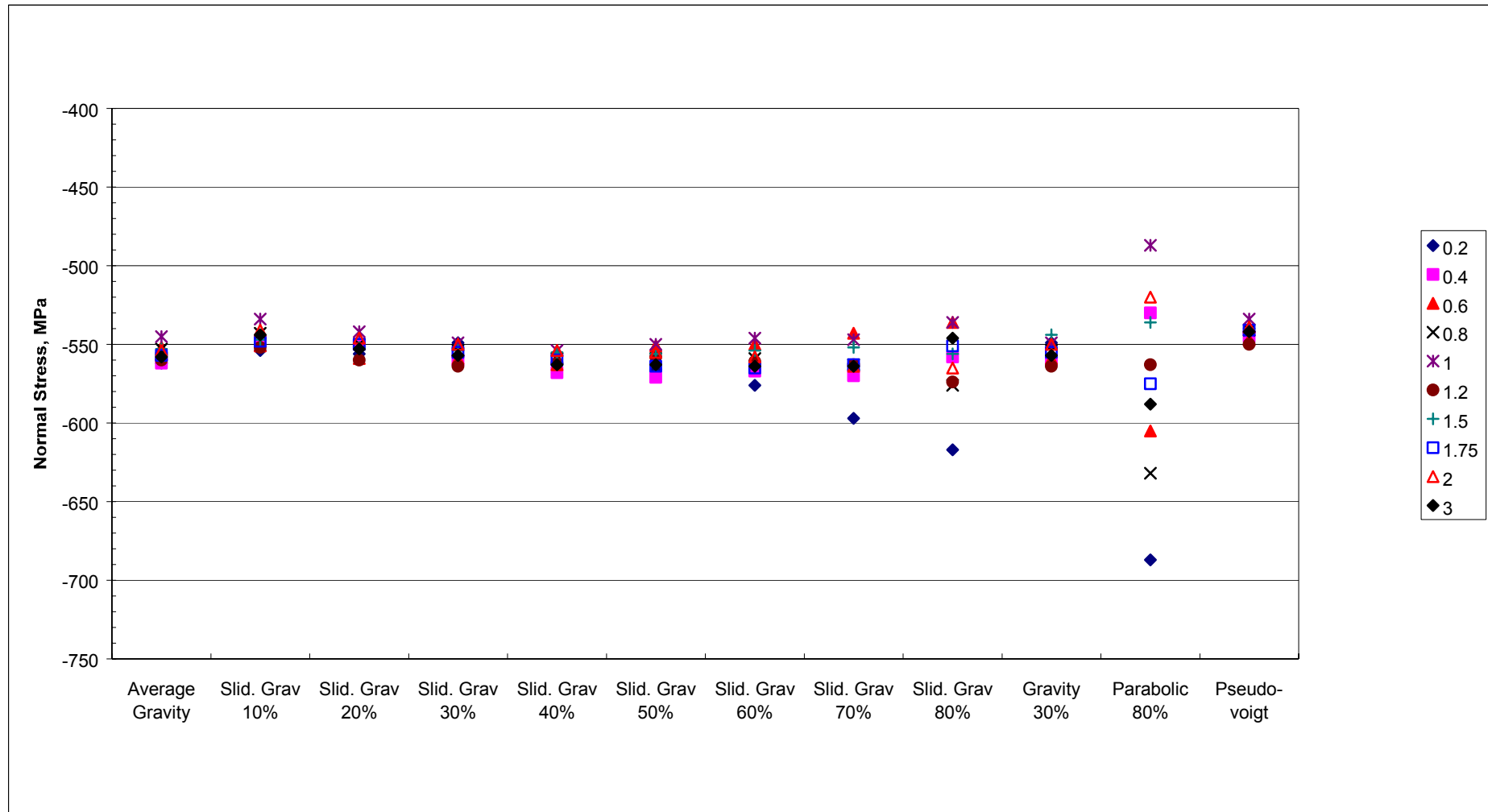


Figure A10 Normal stress distribution for count time sensitivity tests on the spring steel

**APPENDIX B - DETAILED RESULTS FOR HEAT-TREATED
ALUMINIUM**

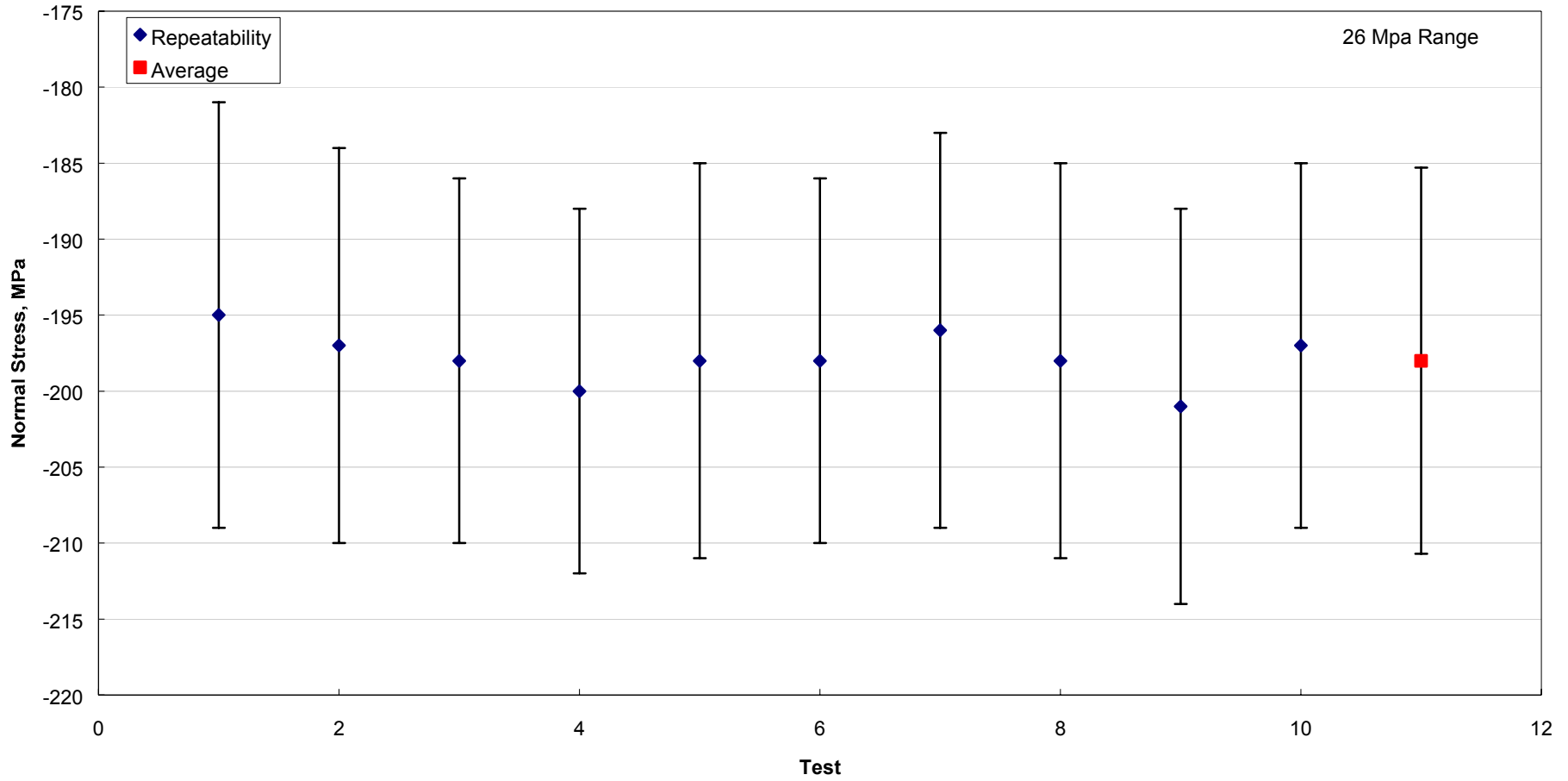


Figure B1 Repeatability of heat-treated aluminium measurements

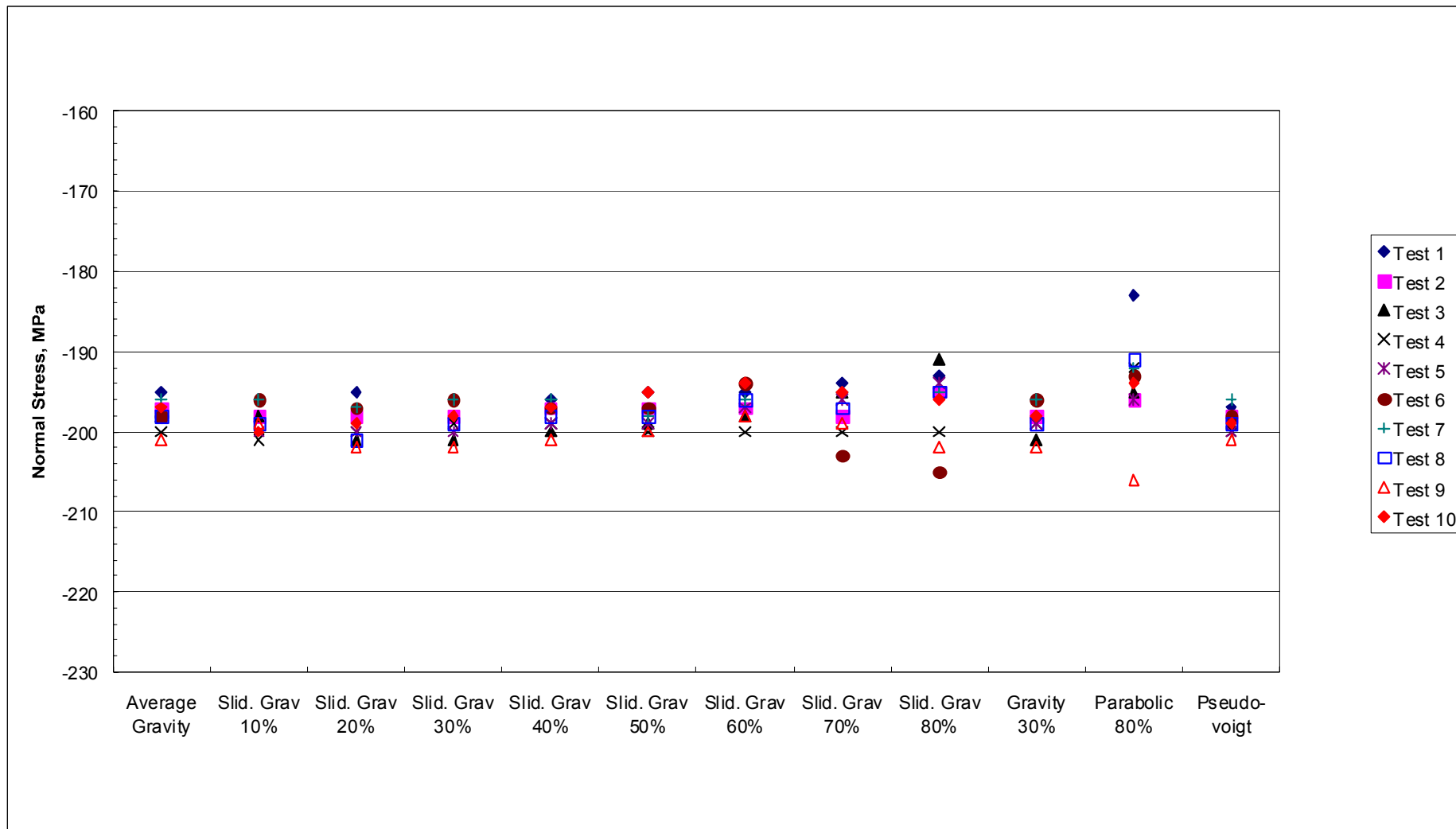


Figure B2 Normal stress distribution for repeatability tests on the heat-treated aluminium, showing the results for all support peak-fitting routines

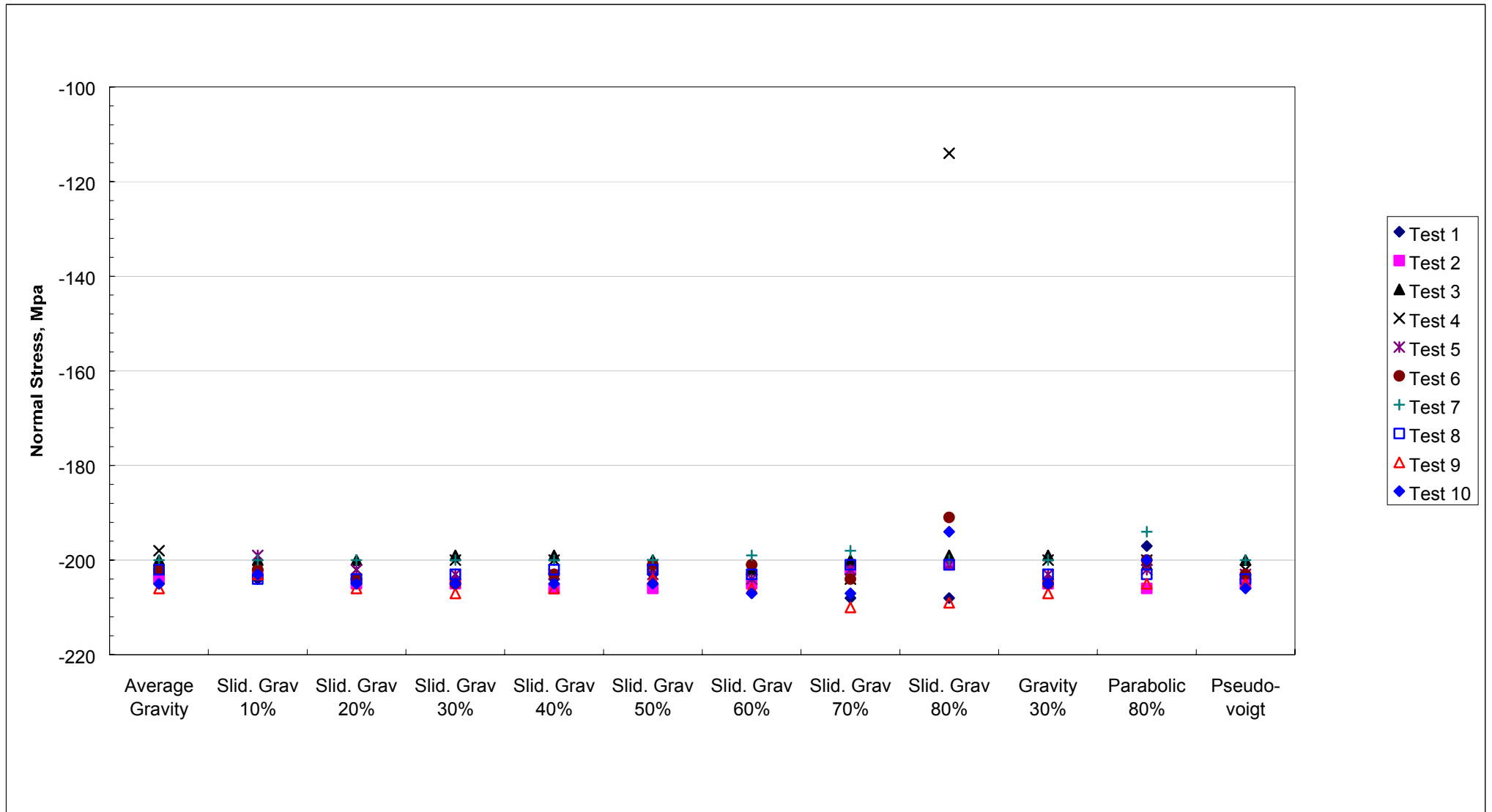


Figure B3 Normal stress distribution for repeatability (removing the specimen between tests) tests on the heat-treated aluminium

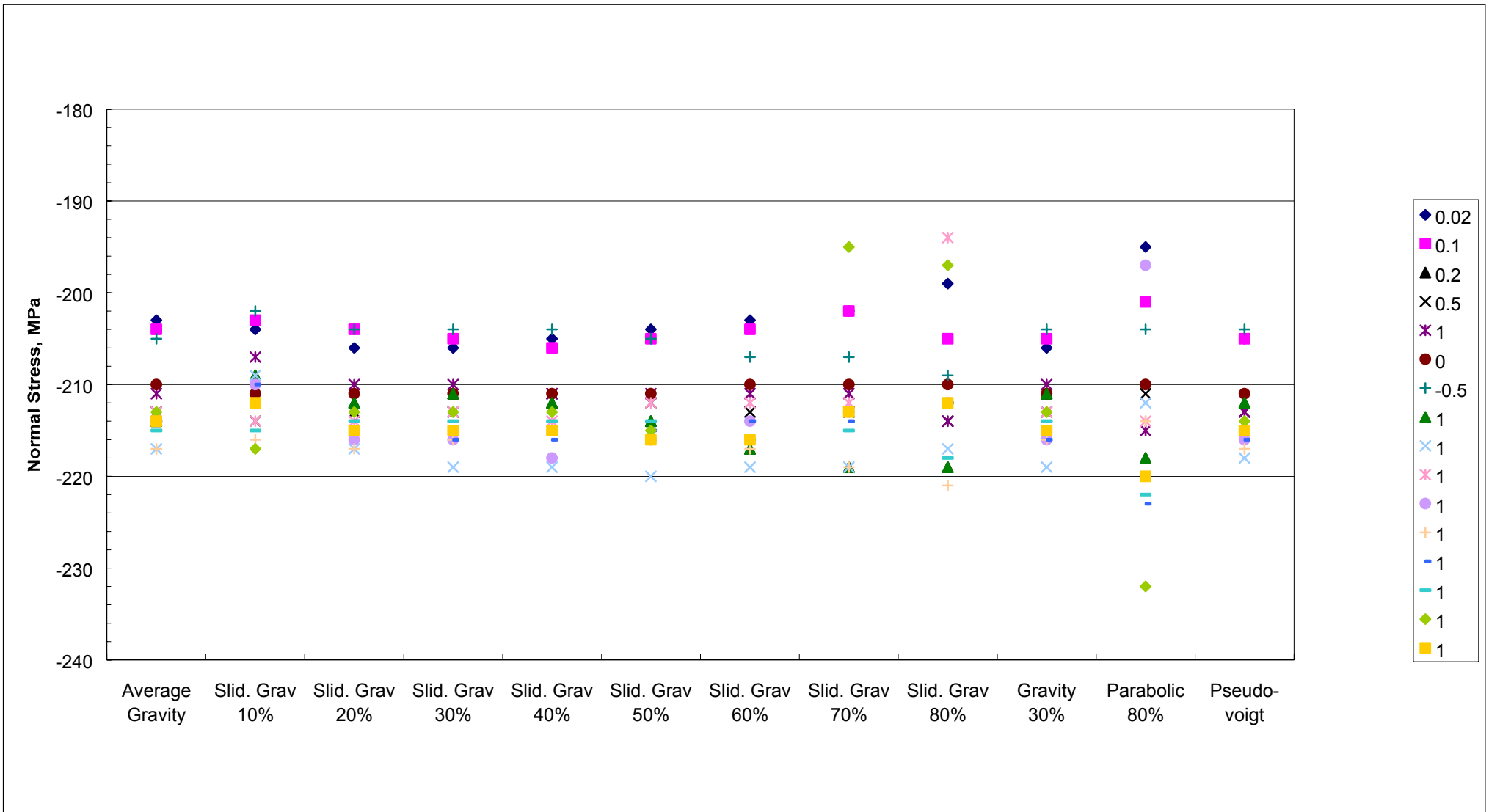


Figure B4 Normal stress distribution for height sensitivity tests on the heat-treated aluminium

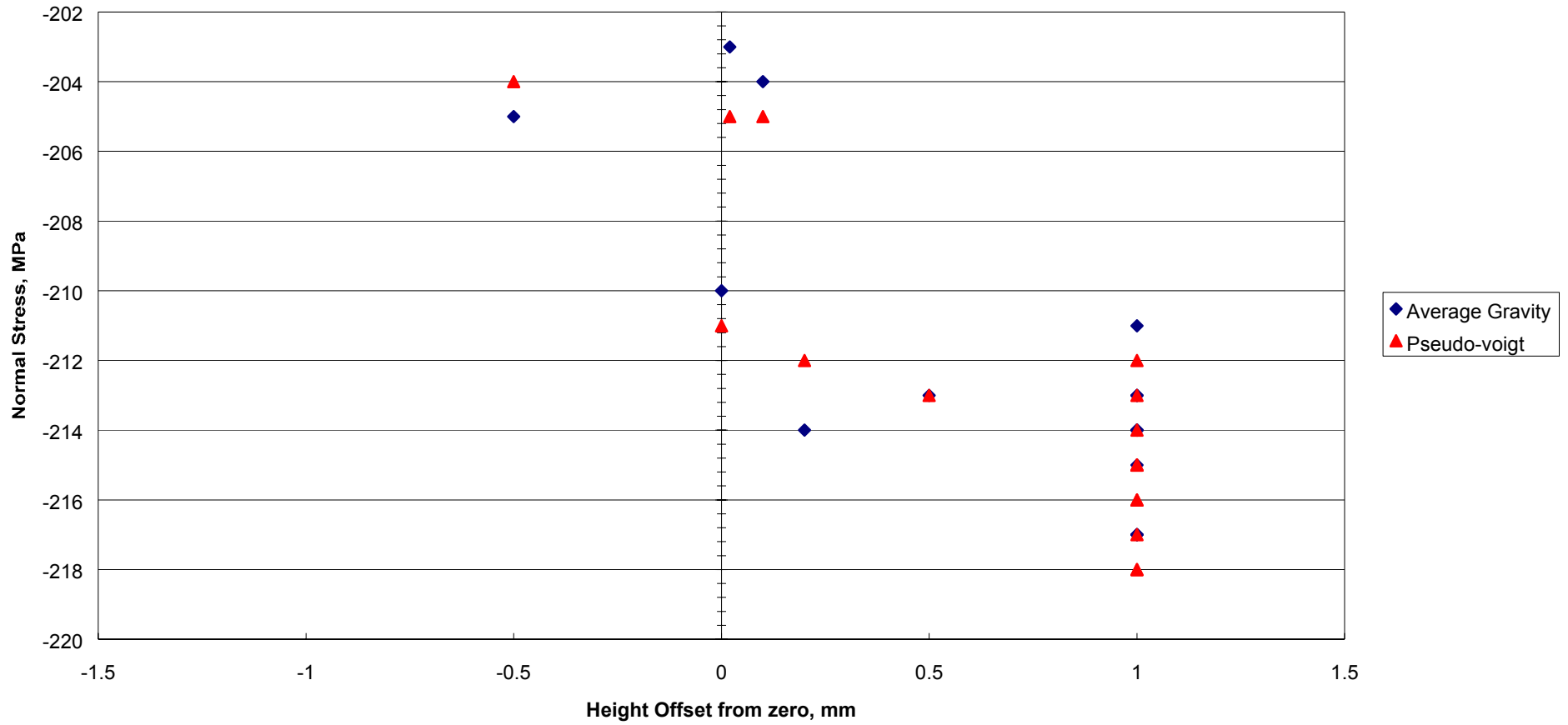


Figure B5 Normal stress distribution for height sensitivity tests on the heat-treated aluminium

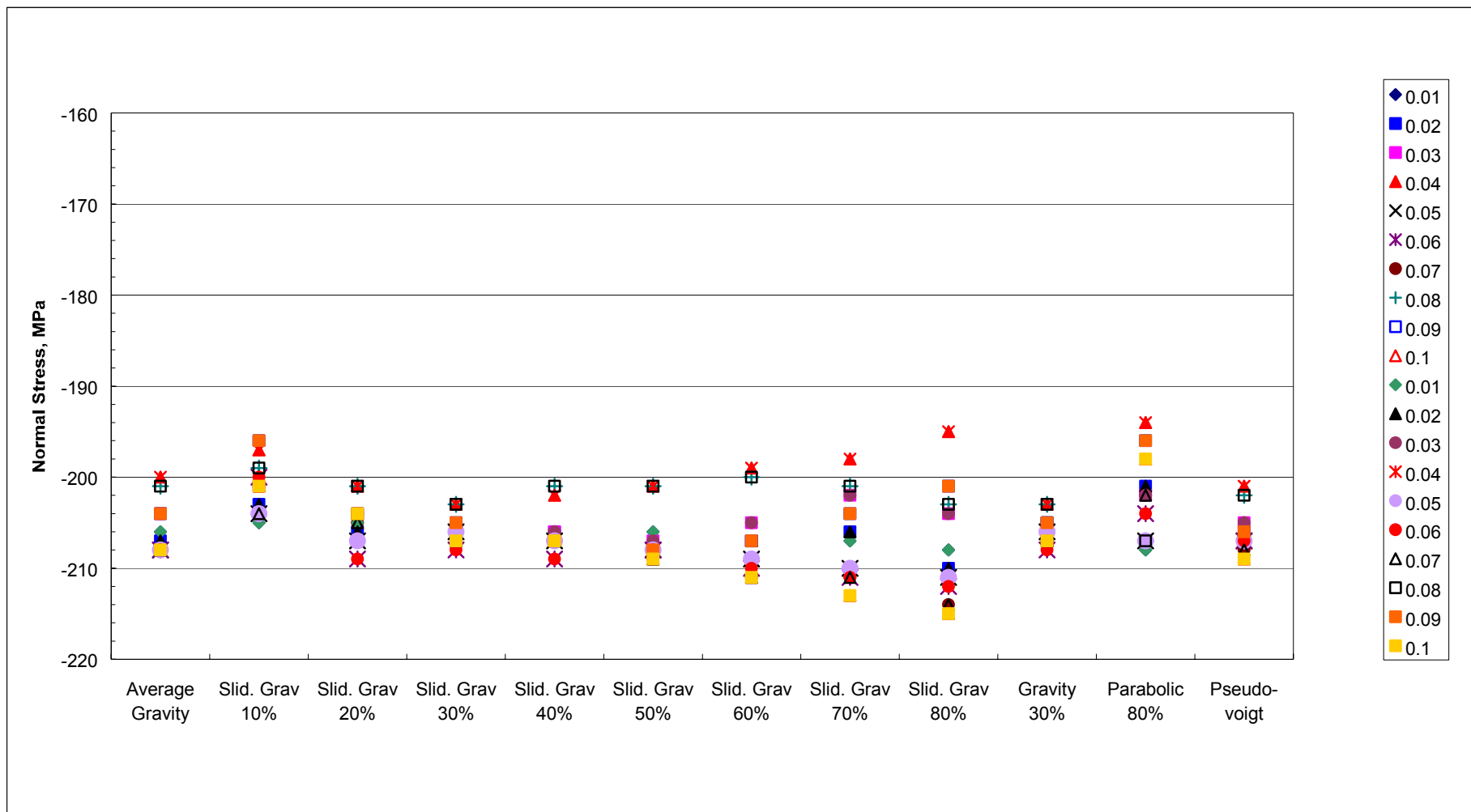


Figure B6 Normal stress distribution for step size sensitivity tests on the heat-treated aluminium

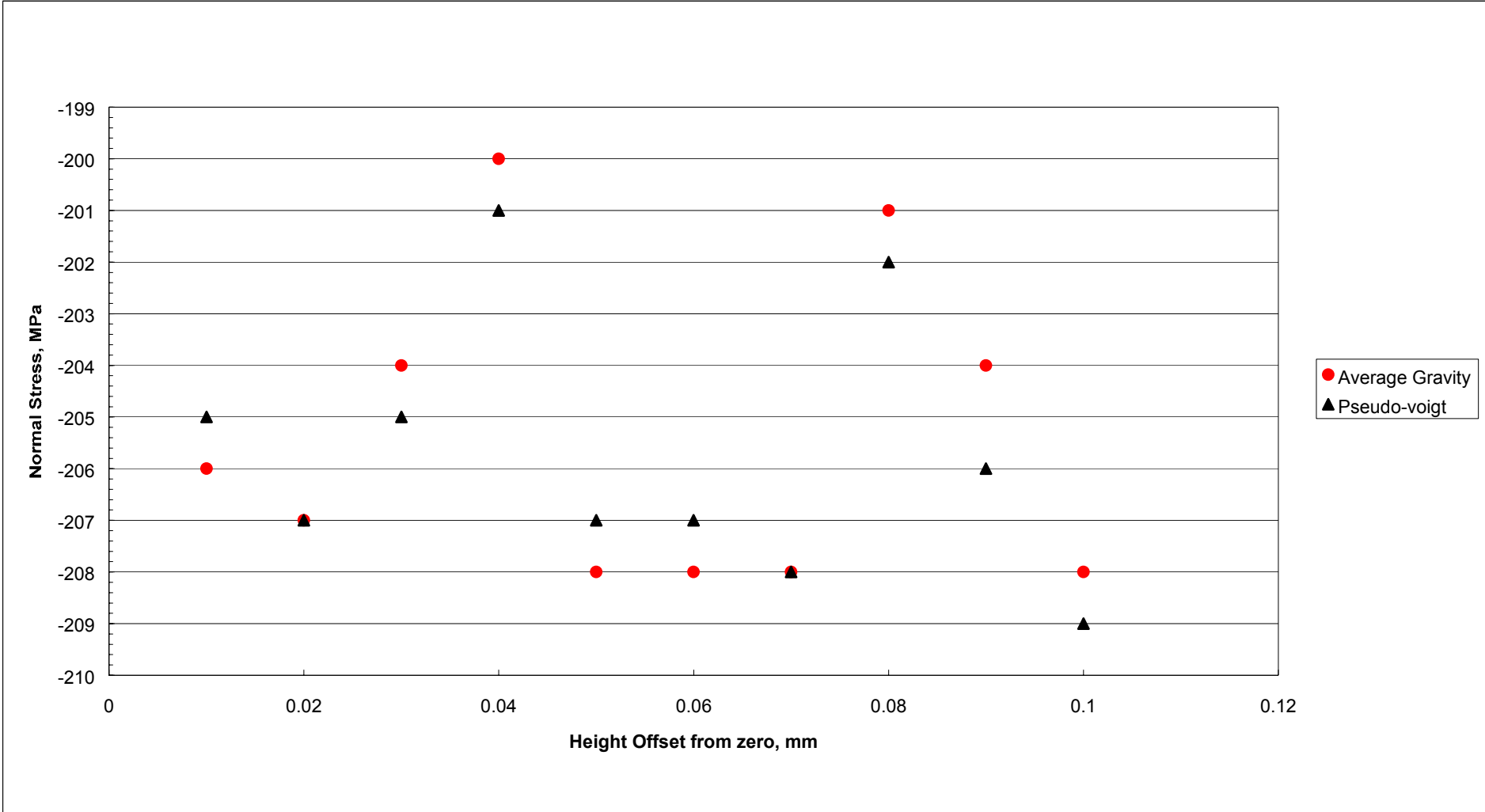


Figure B7 Normal stress distribution for step size sensitivity tests on the heat-treated aluminium

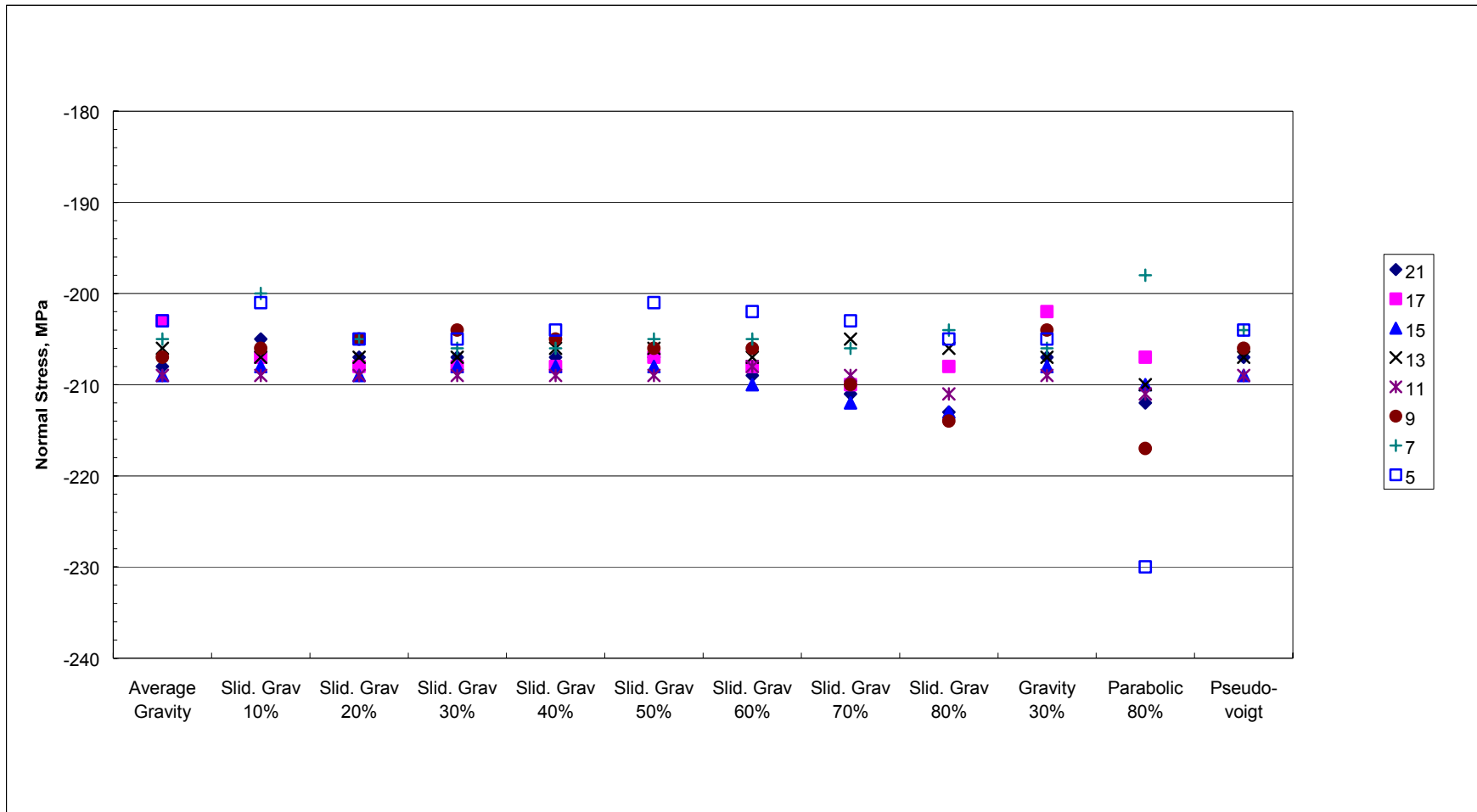


Figure B8 Normal stress distribution for psi tilts sensitivity tests on the heat-treated aluminium

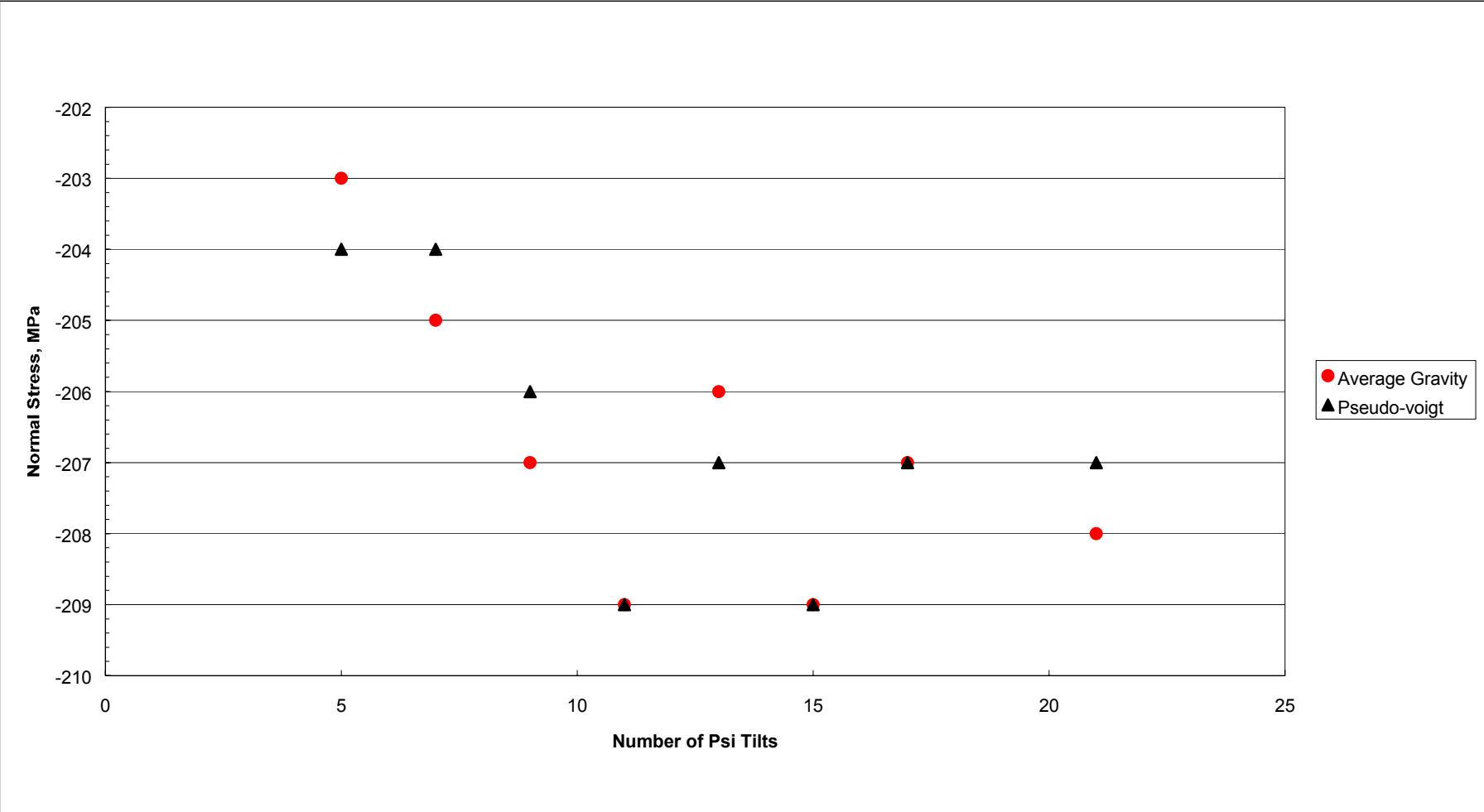


Figure B9 Normal stress distribution for psi tilts sensitivity tests on the heat-treated aluminium

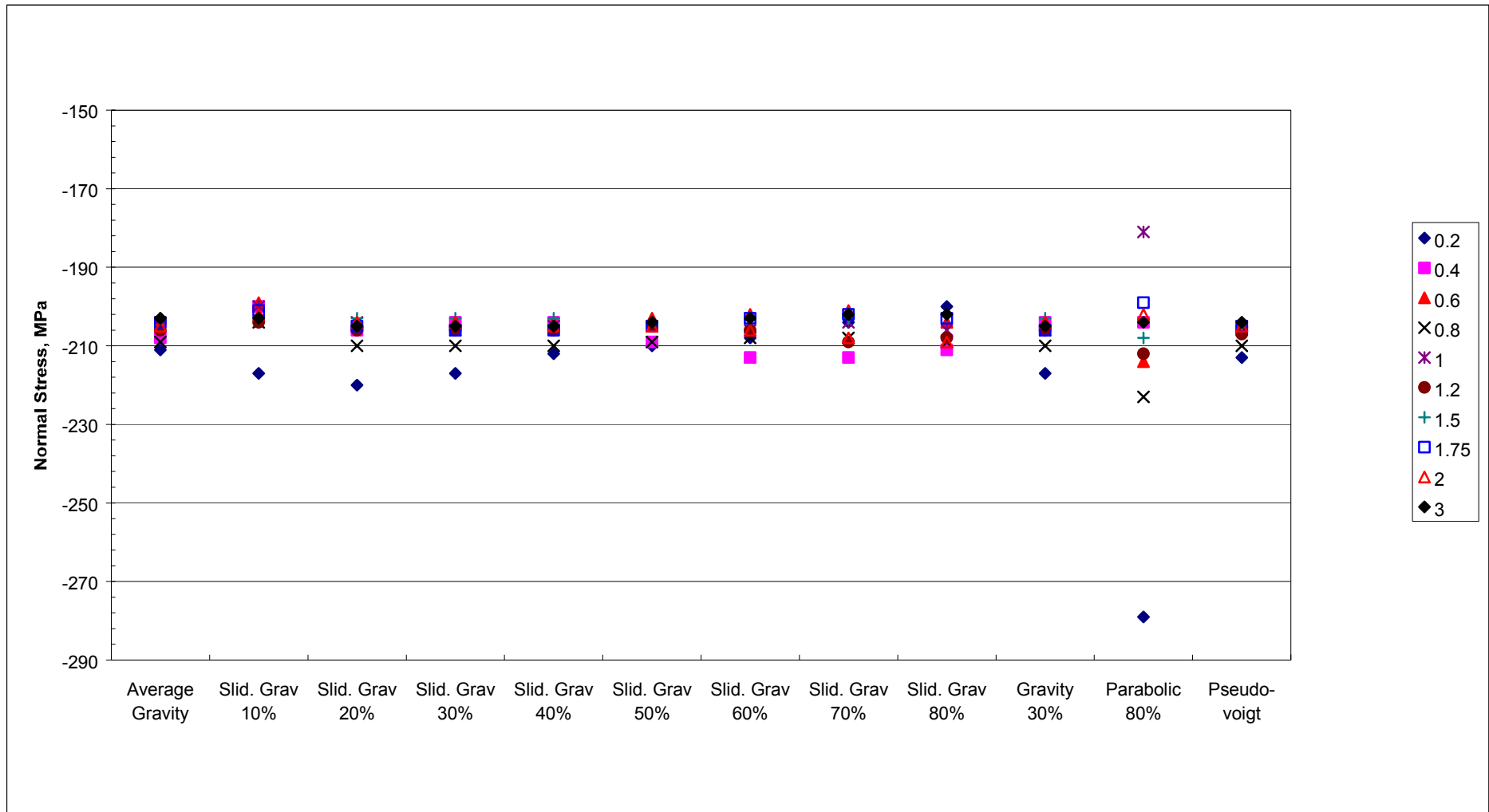


Figure B10 Normal stress distribution for count time sensitivity tests on the heat-treated aluminium

APPENDIX C - DETAILED RESULTS FOR GROUND TITANIUM

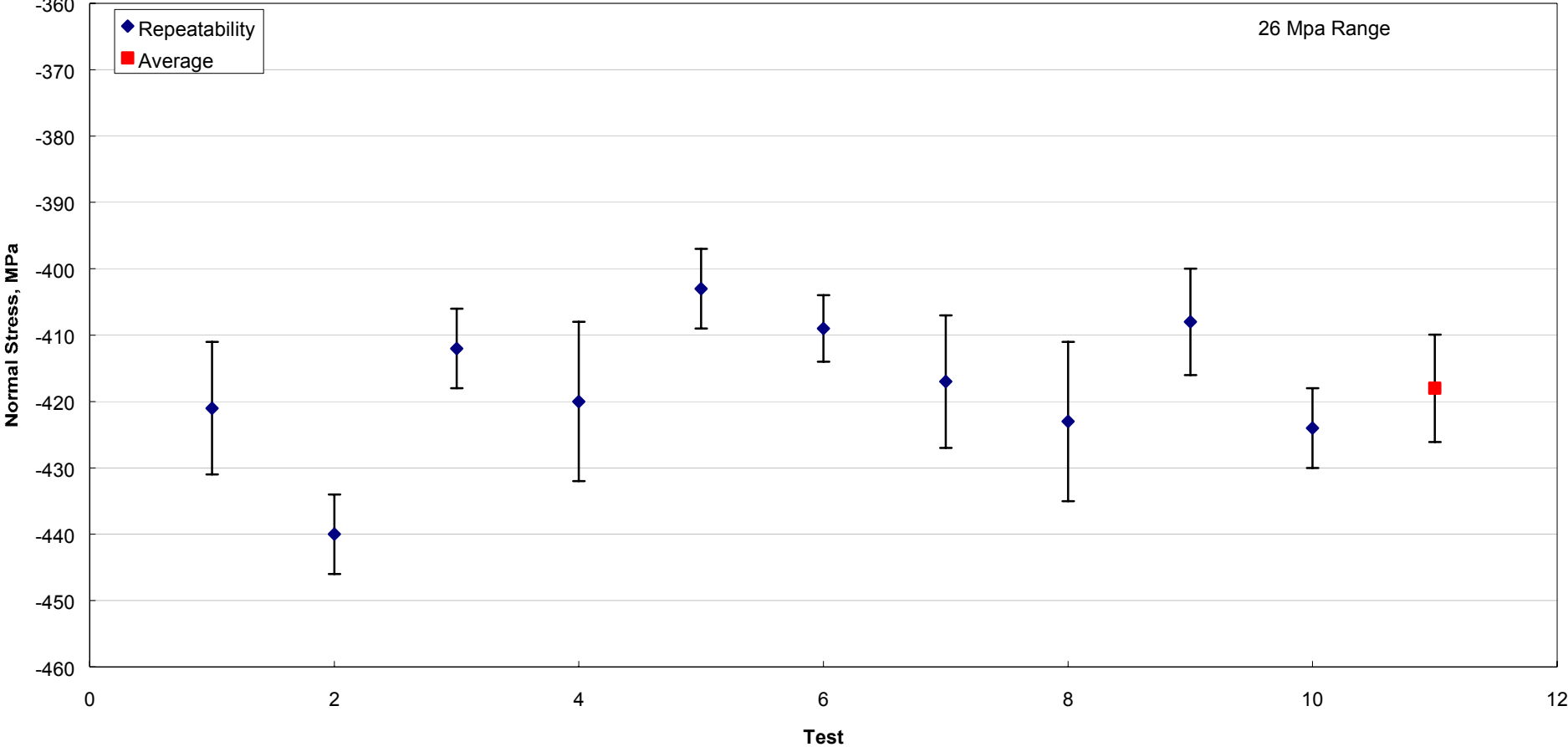


Figure C1 Repeatability of ground titanium measurements

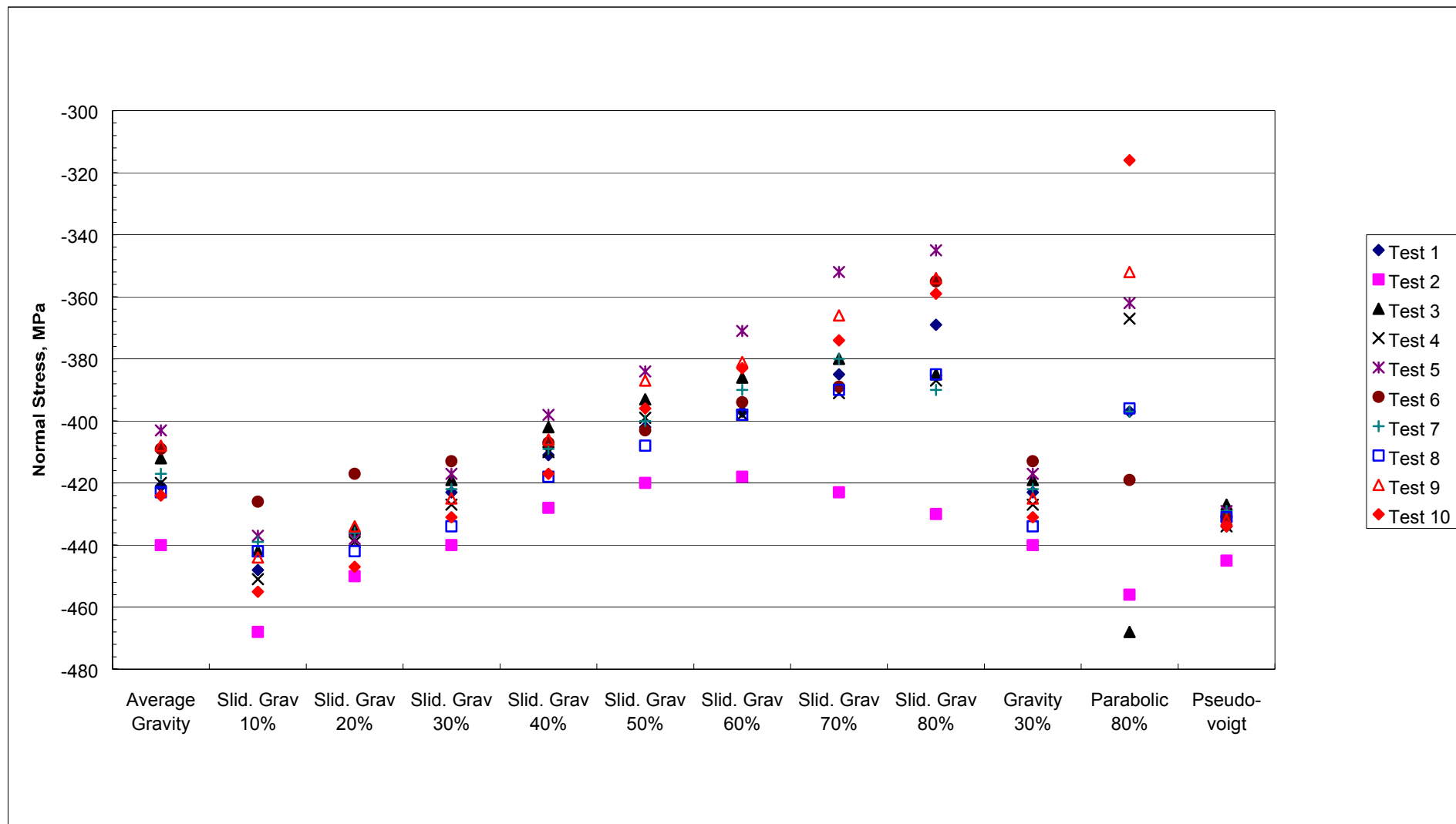


Figure C2 Normal stress distribution for repeatability tests on the ground titanium, showing the results for all supported peak-fitting routines

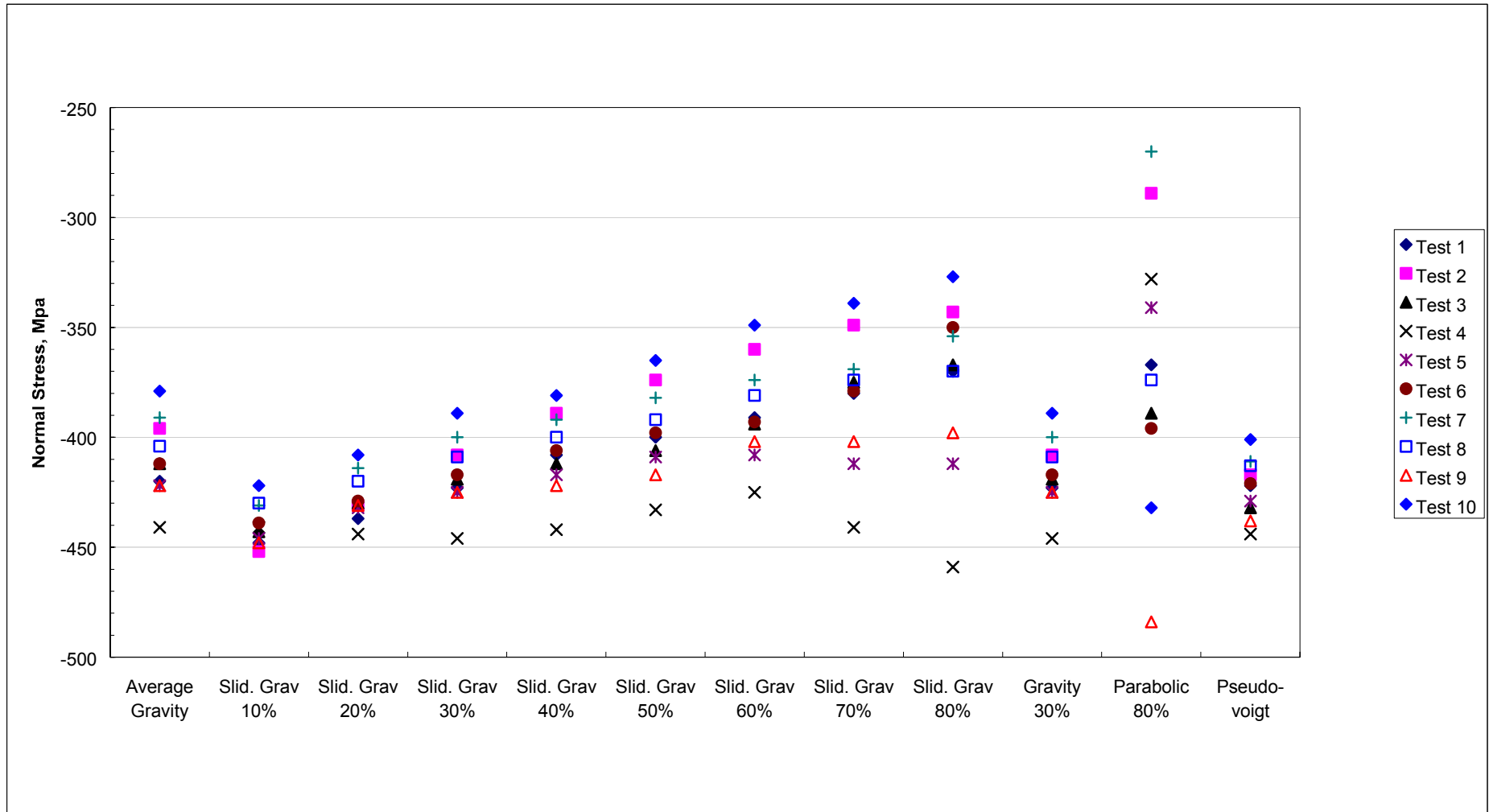


Figure C3 Normal stress distribution for repeatability (removing the specimen between tests) tests on the ground titanium

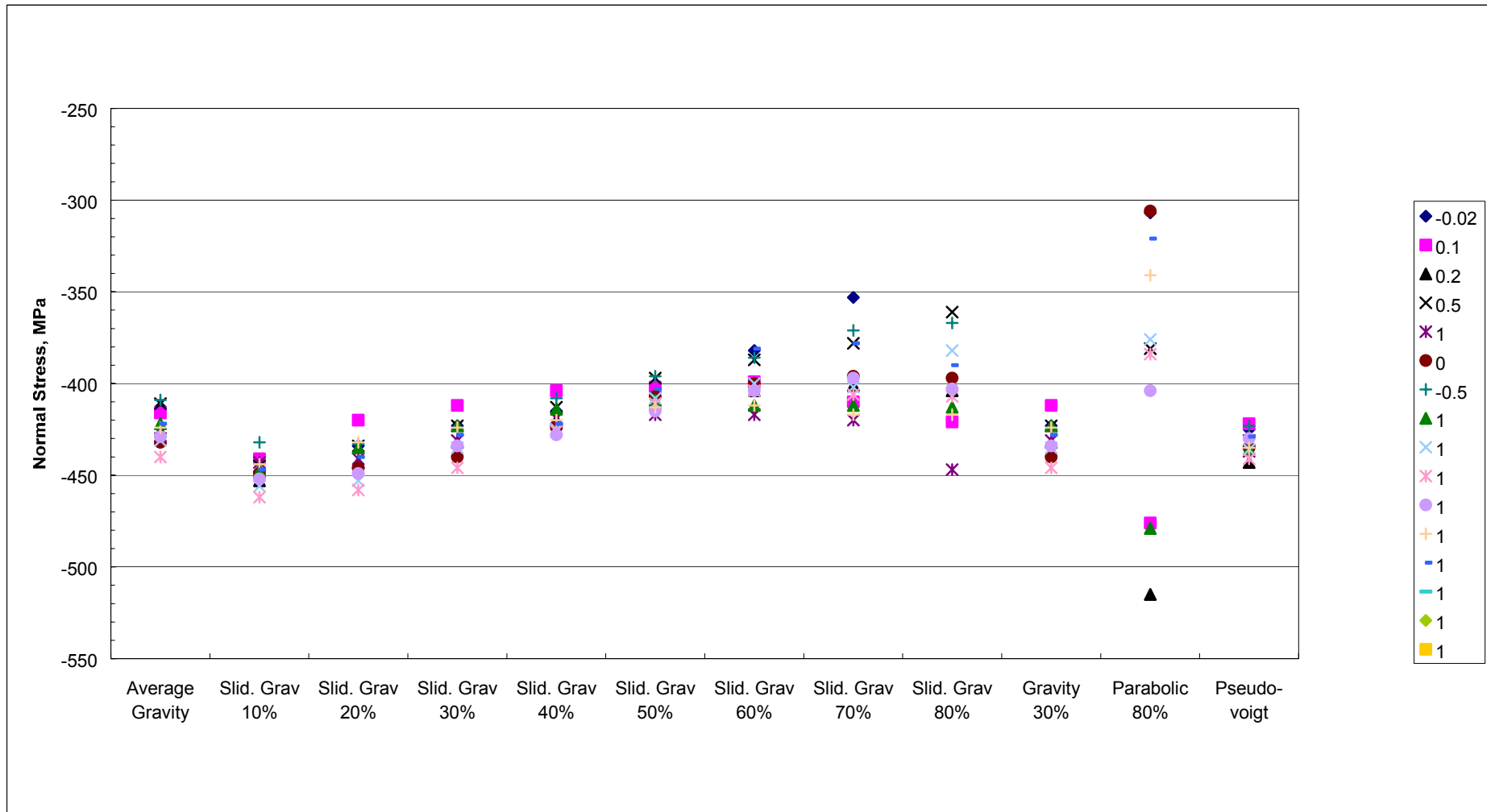


Figure C4 Normal stress distribution for height sensitivity tests on the ground titanium

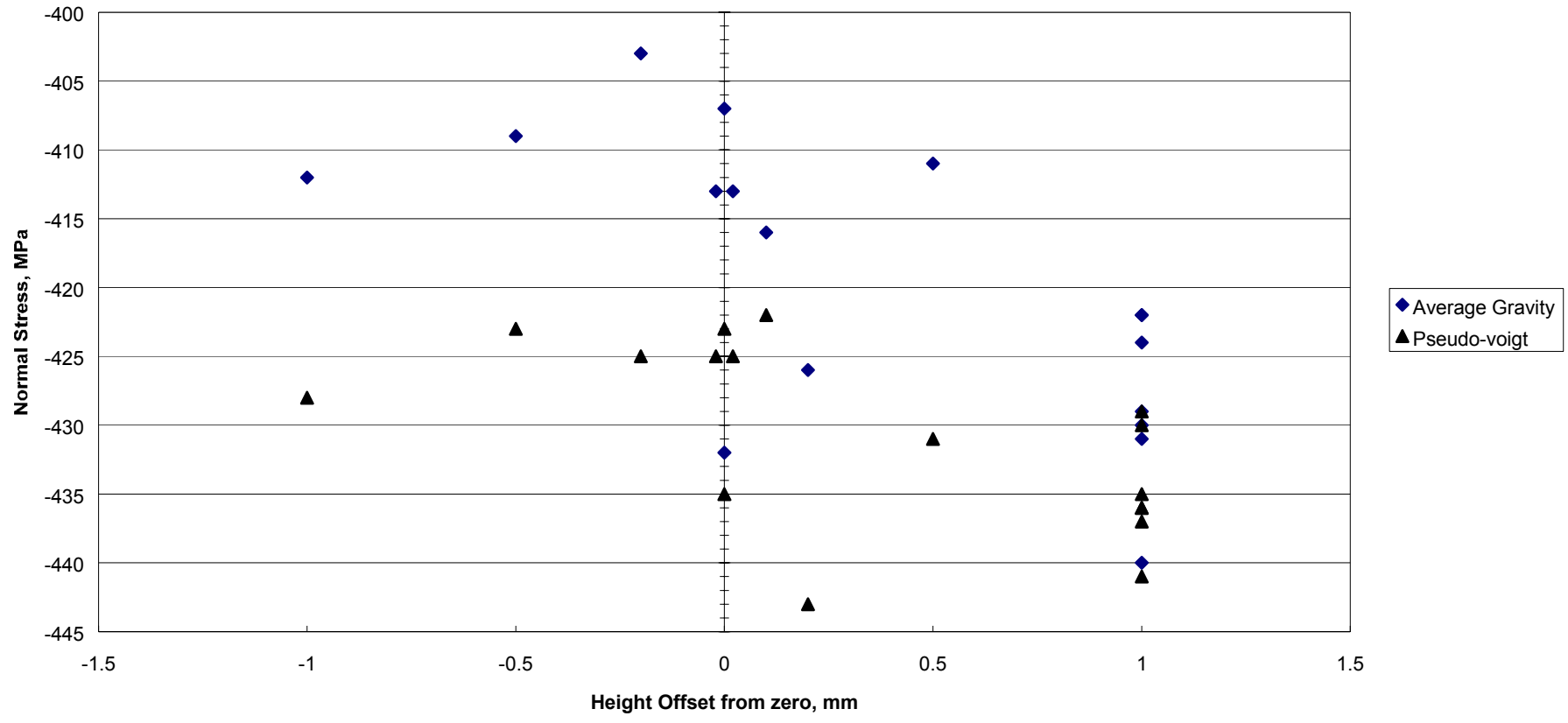


Figure C5 Normal stress distribution for height sensitivity tests on the ground titanium

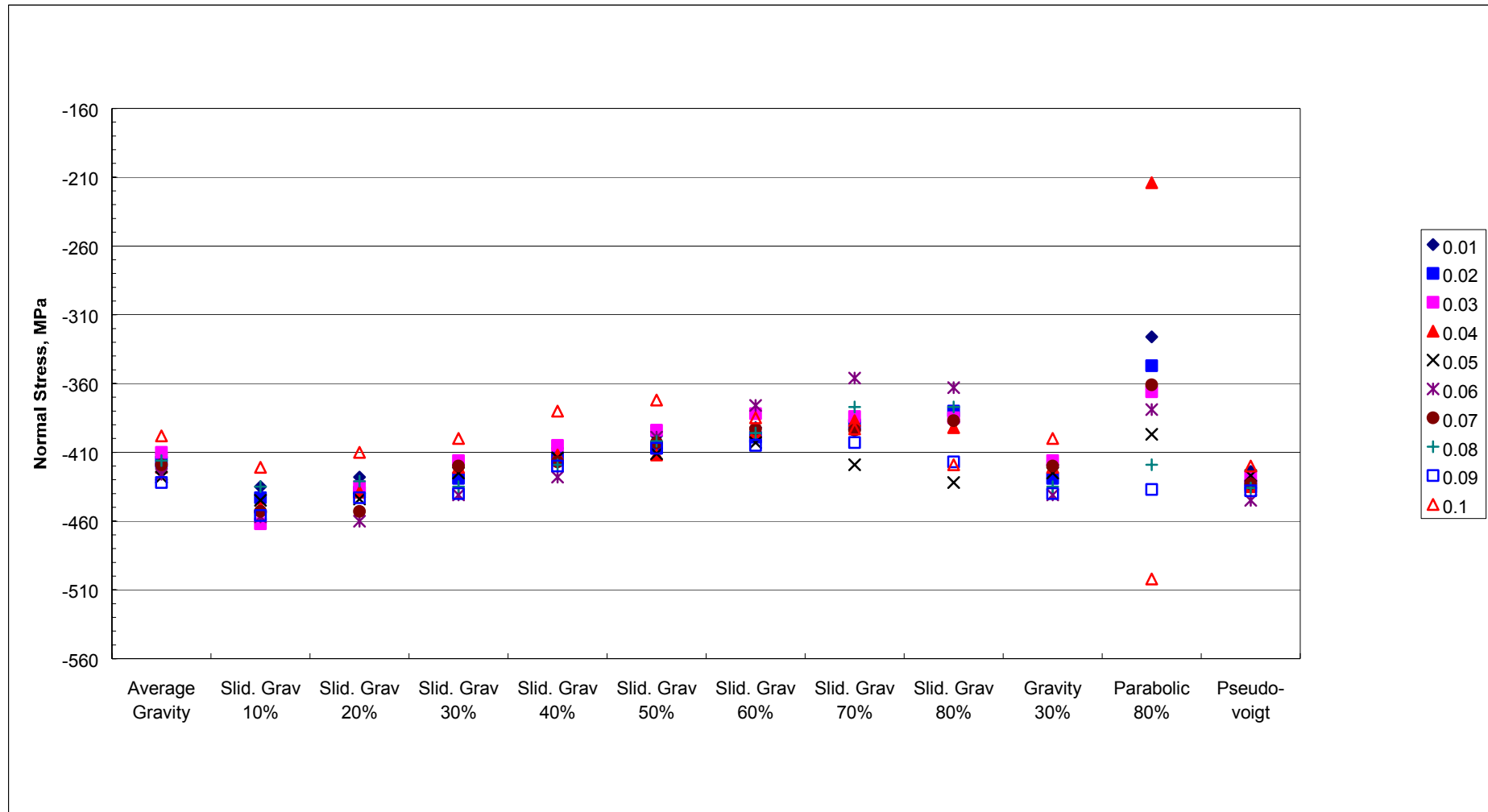


Figure C6 Normal stress distribution for step size sensitivity tests on the ground titanium

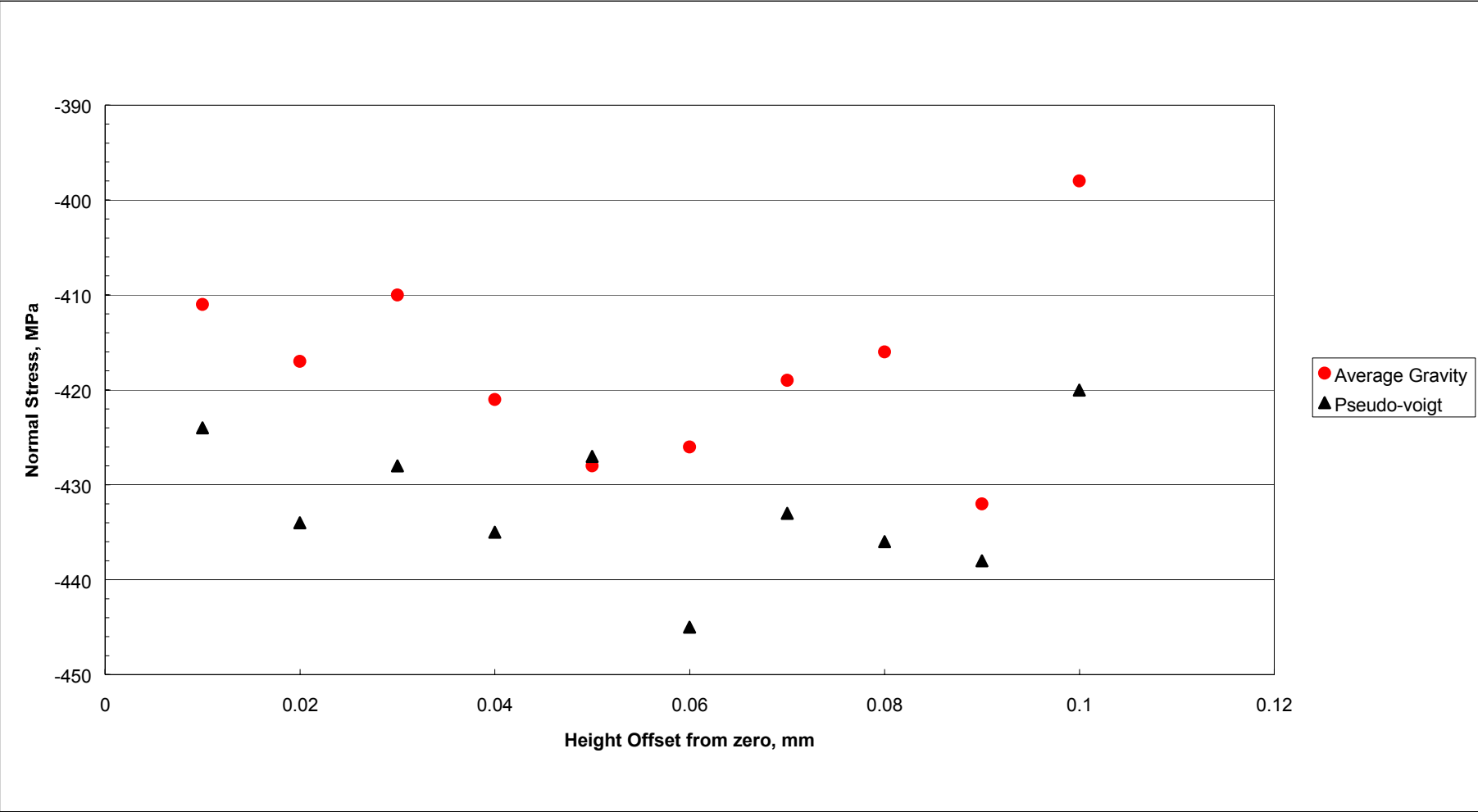


Figure C7 Normal stress distribution for step size sensitivity tests on the ground titanium

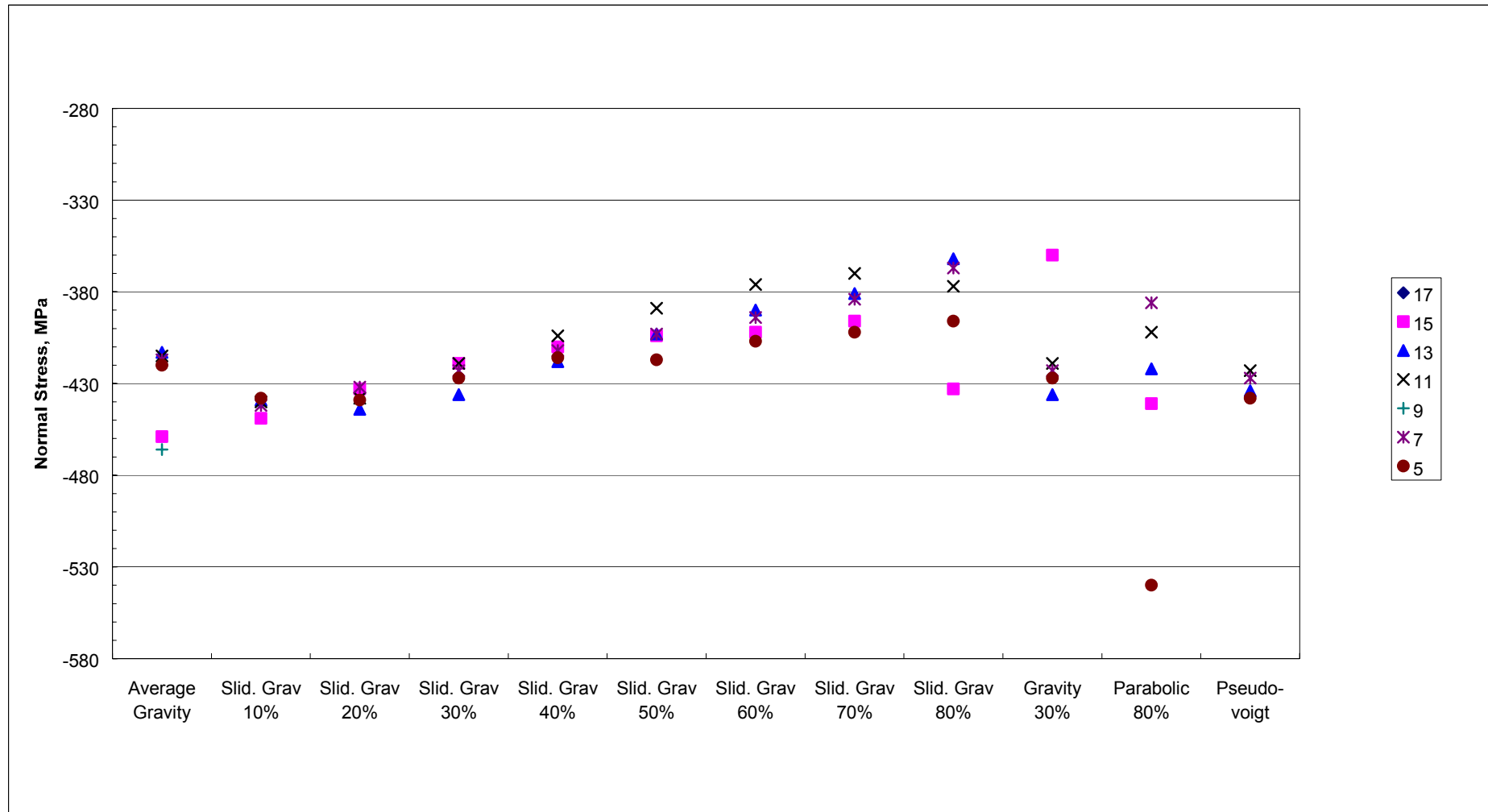


Figure C8 Normal stress distribution for psi tilt sensitivity tests on the ground titanium

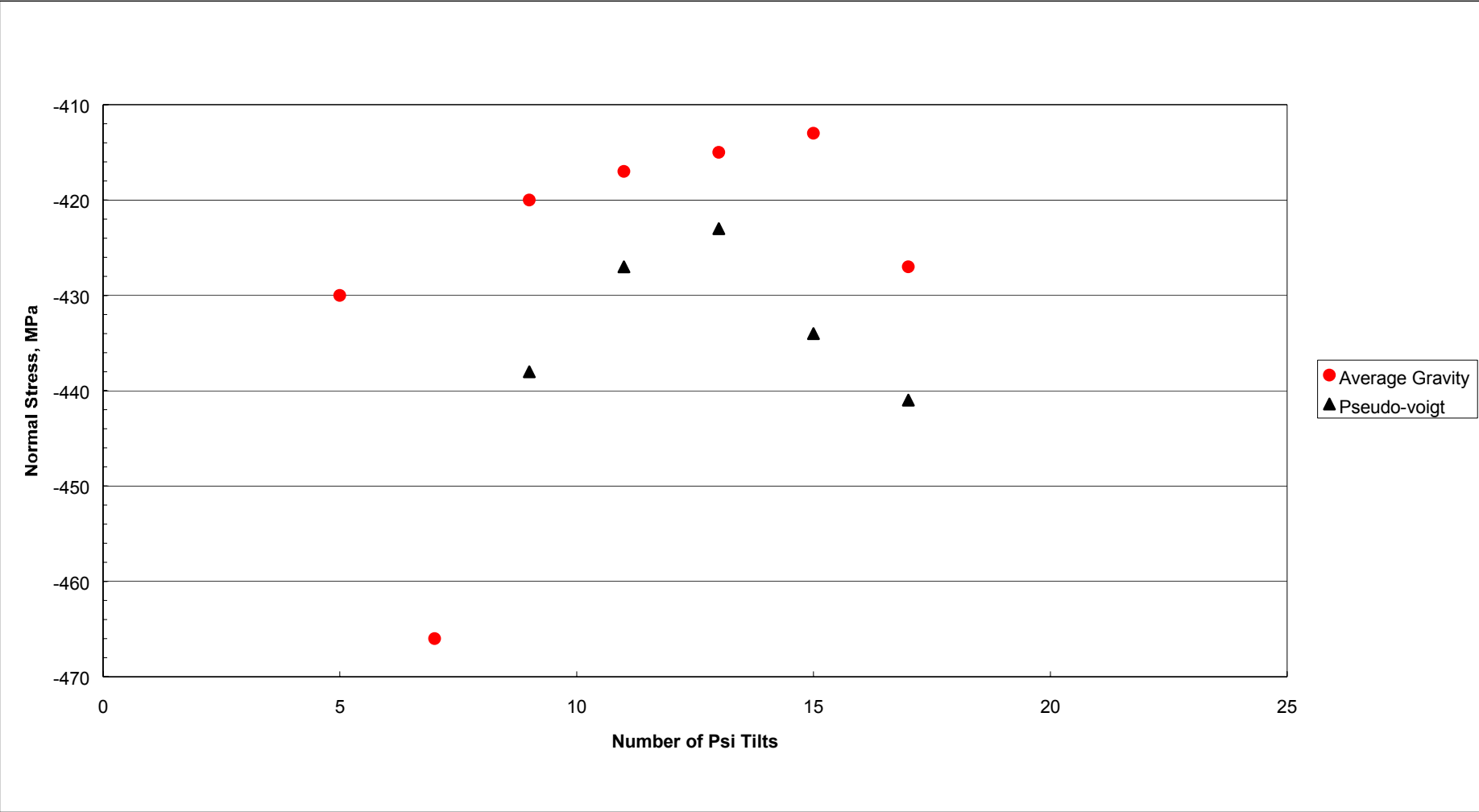


Figure C9 Normal stress distribution for psi tilts sensitivity tests on the ground titanium

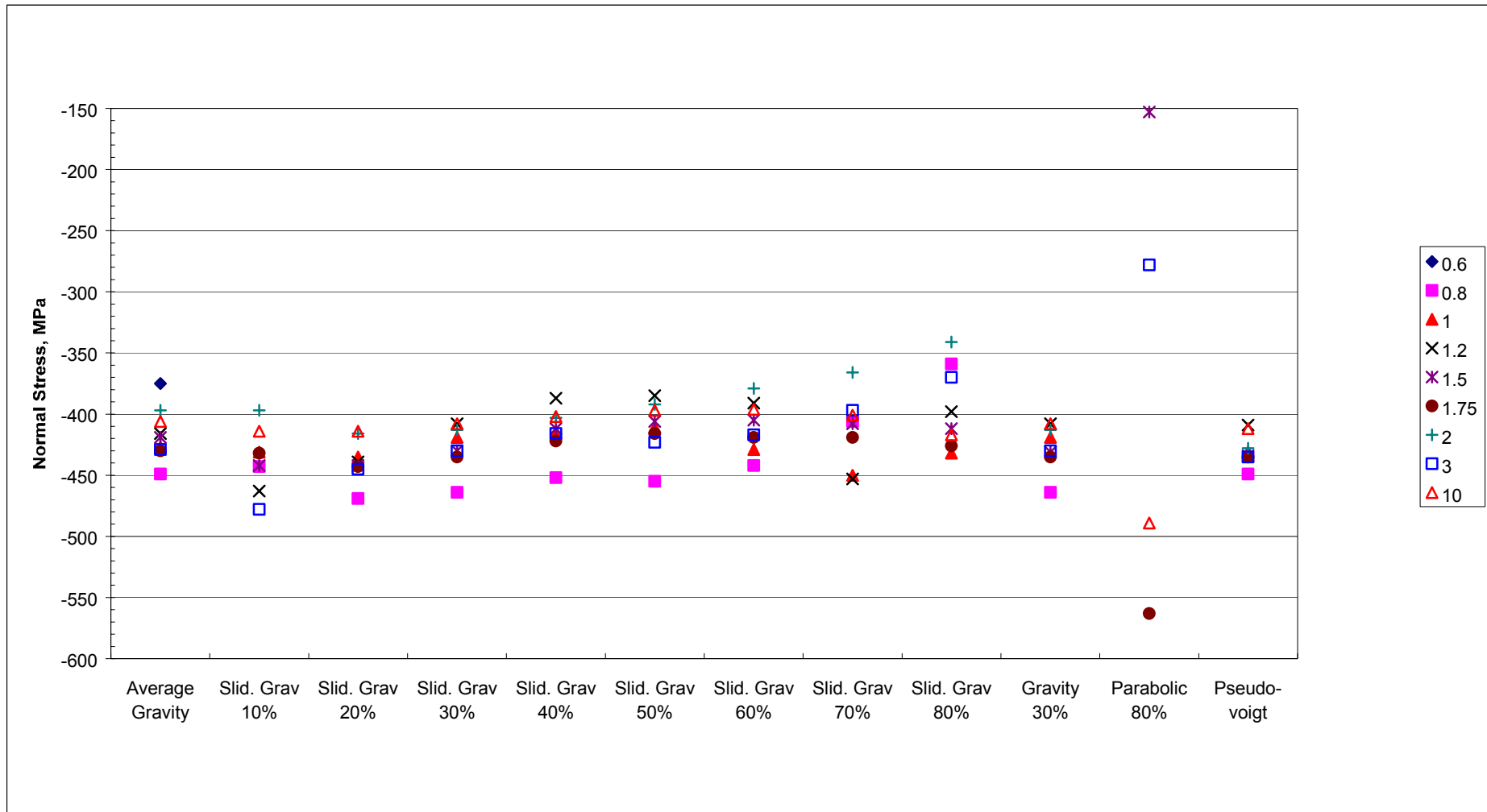


Figure C10 Normal stress distribution for count time sensitivity tests on the ground titanium

**APPENDIX D – NUMERICAL DATA FOR ALL TESTS
CONDUCTED**

Table D1 Full numerical data for tests conducted on the shot-peened spring steel specimen.

Investigation	Test ID	Test Settings							Sliding Gravity									Ave. Grav.	Gravity	Para	P-V Fit
		Start	Stop	Step	Time	Height	Psi	Range	Threshold												
		°20	°20	°20	s	mm	Tilts	°	10%	20%	30%	40%	50%	60%	70%	80%	NA				
Repeatability	RSC30RSD1	150	159.8	0.02	1.5	0	9	9.8	-535	-544	-548	-551	-555	-559	-563	-569	-553	-548	-537	-536	
Repeatability	RSC30RSD2	150	159.8	0.02	1.5	0	9	9.8	-530	-538	-541	-550	-553	-551	-553	-549	-545	-541	-548	-529	
Repeatability	RSC30RSD3	150	159.8	0.02	1.5	0	9	9.8	-530	-538	-548	-554	-556	-555	-558	-554	-547	-548	-531	-529	
Repeatability	RSC30RSD4	150	159.8	0.02	1.5	0	9	9.8	-529	-541	-548	-547	-542	-540	-538	-533	-540	-548	-575	-530	
Repeatability	RSC30RSD5	150	159.8	0.02	1.5	0	9	9.8	-540	-548	-550	-555	-555	-555	-558	-553	-550	-550	-596	-539	
Repeatability	RSC30RSD6	150	159.8	0.02	1.5	0	9	9.8	-536	-544	-546	-549	-550	-550	-555	-235	-542	-546	-504	-531	
Repeatability	RSC30RSD7	150	159.8	0.02	1.5	0	9	9.8	-533	-542	-547	-553	-555	-553	-541	-536	-545	-547	-527	-533	
Repeatability	RSC30RSD8	150	159.8	0.02	1.5	0	9	9.8	-538	-548	-546	-550	-551	-552	-559	-554	-548	-546	-574	-535	
Repeatability	RSC30RSD9	150	159.8	0.02	1.5	0	9	9.8	-533	-544	-546	-550	-558	-560	-565	-566	-551	-546	-545	-533	
Repeatability	RSC30RSD10	150	159.8	0.02	1.5	0	9	9.8	-529	-538	-543	-552	-556	-560	-550	-549	-550	-543	-538	-528	
Repeatability 2	RSC30RSD11	150	159.8	0.02	2	0	9	9.8	-529	-542	-549	-551	-550	-551	-548	-552	-547	-549	-528	-533	
Repeatability 2	RSC30RSD12	150	159.8	0.02	2	0	9	9.8	-538	-549	-554	-551	-549	-545	-548	-559	-547	-554	-550	-535	
Repeatability 2	RSC30RSD13	150	159.8	0.02	2	0	9	9.8	-533	-538	-541	-547	-551	-547	-554	-545	-543	-541	-512	-529	
Repeatability 2	RSC30RSD14	150	159.8	0.02	2	0	9	9.8	-525	-537	-541	-545	-546	-546	-552	-586	-537	-541	-552	-525	
Repeatability 2	RSC30RSD15	150	159.8	0.02	2	0	9	9.8	-536	-547	-549	-551	-558	-564	-567	-571	-554	-549	-536	-538	
Repeatability 2	RSC30RSD16	150	159.8	0.02	2	0	9	9.8	-552	-555	-561	-567	-570	-567	-564	-568	-563	-561	-585	-550	
Repeatability 2	RSC30RSD17	150	159.8	0.02	2	0	9	9.8	-545	-549	-557	-562	-563	-559	-563	-566	-555	-557	-556	-543	
Repeatability 2	RSC30RSD18	150	159.8	0.02	2	0	9	9.8	-553	-559	-562	-564	-560	-567	-570	-572	-562	-562	-563	-550	
Repeatability 2	RSC30RSD19	150	159.8	0.02	2	0	9	9.8	-545	-554	-557	-559	-562	-561	-559	-571	-558	-557	-545	-543	
Repeatability 2	RSC30RSD20	150	159.8	0.02	2	0	9	9.8	-552	-555	-560	-562	-559	-559	-561	-557	-557	-560	-585	-546	
Height	RSC30RS21	150	159.8	0.02	2	0.02	9	9.8	-538	-559	-558	-558	-559	-558	-555	-576	-554	-559	-596	-542	
Height	RSC30RS22	150	159.8	0.02	2	0.1	9	9.8	-541	-553	-558	-564	-563	-555	-249	-247	-556	-558	-579	-545	
Height	RSC30RS23	150	159.8	0.02	2	0.2	9	9.8	-535	-551	-564	-569	-570	-561	-563	-561	-558	-564	-554	-539	
Height	RSC30RS24	150	159.8	0.02	2	0.5	9	9.8	-548	-562	-565	-562	-563	-567	-581	-594	-565	-565	-579	-548	
Height	RSC30RS25	150	159.8	0.02	2	1	9	9.8	-558	-565	-572	-574	-574	-576	-582	-577	-570	-572	-619	-556	
Height	RSC30RS26	150	159.8	0.02	2	0	9	9.8	-551	-563	-568	-569	-570	-563	-557	-545	-563	-568	-593	-552	
Height	RSC30RS27	150	159.8	0.02	2	-0.5	9	9.8	-545	-550	-550	-553	-561	-562	-271	-272	-552	-550	-579	-533	
Height	RSC30RS28	150	159.8	0.02	2	-1	9	9.8	-540	-549	-548	-552	-559	-563	-561	-565	-552	-548	-562	-537	
Height	RSC30RS29	150	159.8	0.02	2	-0.2	9	9.8	-542	-552	-558	-561	-561	-552	-546	-538	-552	-558	-510	-540	
Height	RSC30RS30	150	159.8	0.02	2	-0.02	9	9.8	-537	-544	-554	-557	-559	-560	-561	-561	-554	-554	-532	-540	
Height	RSC30RS31	150	159.8	0.02	2	0	9	9.8	-548	-555	-558	-561	-564	-554	-555	-512	-556	-558	-528	-541	
Height	RSC30RS32	150	159.8	0.02	2	1	9	9.8	-558	-565	-571	-580	-590	-592	-590	-594	-581	-571	-580	-557	
Height	RSC30RS33	150	159.8	0.02	2	1	9	9.8	-569	-573	-576	-579	-582	-582	-579	-551	-576	-576	-558	-566	
Height	RSC30RS34	150	159.8	0.02	2	1	9	9.8	-558	-569	-575	-579	-578	-577	-570	-568	-572	-575	-544	-559	

Investigation	Test ID	Test Settings							Sliding Gravity									Ave. Grav.	Gravity	Para	P-V Fit
		Start	Stop	Step	Time	Height	Psi	Range	Threshold												
		°2θ	°2θ	°2θ	s	mm	Tilts	°	10%	20%	30%	40%	50%	60%	70%	80%	NA				
Height	RSC30RS35	150	159.8	0.02	2	1	9	9.8	-562	-573	-582	-587	-582	-574	-573	-177	-577	-582	-536		
Height	RSC30RS36	150	159.8	0.02	2	1	9	9.8	-568	-573	-580	-586	-589	-589	-584	-597	-582	-580	-608	-566	
Height	RSC30RS37	150	159.8	0.02	2	1	9	9.8	-566	-576	-577	-578	-568	-553	-196	-210	-571	-577	-579	-556	
Height	RSC30RS38	150	159.8	0.02	2	1	9	9.8	-564	-568	-573	-577	-576	-572	-564	-555	-569	-573	-558	-557	
Height	RSC30RS39	150	159.8	0.02	2	1	9	9.8	-562	-571	-575	-576	-573	-567	-556	-582	-570	-575	-566	-559	
Height	RSC30RS40	150	159.8	0.02	2	1	9	9.8	-555	-568	-571	-574	-578	-575	-573	-201	-571	-571	-584	-555	
Height	RSC30RS41	150	159.8	0.02	2	1	9	9.8	-568	-571	-572	-575	-583	-582	-607	-569	-576	-572	-599	-563	
Step Size	RSC30RSD43	150	159.8	0.01	1.5	0	9	9.8	-554	-563	-563	-565	-568	-575	-578	-590	-568	-563	-610	-550	
Step Size	RSC30RSD44	150	159.8	0.03	1.5	0	9	9.8	-554	-555	-559	-566	-565	-568	-576	-569	-561	-559	-550	-549	
Step Size	RSC30RSD45	150	159.8	0.04	1.5	0	9	9.8	-544	-551	-558	-568	-569	-566	-560	-559	-562	-558	-588	-541	
Step Size	RSC30RSD46	150	159.8	0.05	1.5	0	9	9.8	-542	-552	-559	-565	-563	-559	-543	-539	-553	-559	-556	-545	
Step Size	RSC30RSD47	150	159.8	0.06	1.5	0	9	9.8	-551	-553	-553	-558	-559	-562	-564	-559	-557	-553	-554	-542	
Step Size	RSC30RSD48	150	159.8	0.07	1.5	0	9	9.8	-551	-546	-552	-560	-570	-575	-563	-557	-556	-552	-552	-541	
Step Size	RSC30RSD49	150	159.8	0.08	1.5	0	9	9.8	-541	-547	-548	-554	-560	-565	-563	-571	-551	-548	-578	-534	
Step Size	RSC30RSD50	150	159.8	0.09	1.5	0	9	9.8	-551	-549	-549	-549	-559	-561	-576	-216	-557	-549	-552	-540	
Step Size	RSC30RSD51	150	159.8	0.1	1.5	0	9	9.8	-541	-554	-572	-575	-586	-586	-598	-620	-567	-572	-596	-544	
Step Size	RSC30RSD31	150	159.8	0.02	1.5	0	9	9.8	-548	-555	-558	-561	-564	-554	-555	-512	-556	-558	-528	-541	
Psi Tilts	RSC30RSD42	150	159.8	0.02	1.5	0	21	9.8	-551	-561	-568	-568	-569	-569	-567	-574	-565	-568	-589	-552	
Psi Tilts	RSC30RSD53	150	159.8	0.02	1.5	0	17	9.8	-548	-557	-564	-566	-567	-569	-568	-566	-563	-564	-587	-546	
Psi Tilts	RSC30RSD54	150	159.8	0.02	1.5	0	15	9.8	-546	-557	-562	-559	-558	-555	-558	-564	-557	-562	-564	-546	
Psi Tilts	RSC30RSD55	150	159.8	0.02	1.5	0	13	9.8	-544	-546	-555	-560	-564	-569	-569	-575	-557	-555	-583	-541	
Psi Tilts	RSC30RSD56	150	159.8	0.02	1.5	0	11	9.8	-557	-565	-562	-565	-562	-569	-564	-574	-565	-562	-606	-552	
Psi Tilts	RSC30RSD31	150	159.8	0.02	1.5	0	9	9.8	-548	-555	-558	-561	-564	-554	-555	-512	-556	-558	-528	-541	
Psi Tilts	RSC30RSD57	150	159.8	0.02	1.5	0	7	9.8	-547	-555	-556	-559	-558	-557	-562	-190	-556	-556	-525	-541	
Psi Tilts	RSC30RSD58	150	159.8	0.02	1.5	0	5	9.8	-541	-551	-549	-554	-556	-561	-566	-569	-555	-549	-574	-538	
Count Time	RSC30RSD60	150	159.8	0.02	0.2	0	9	9.8	-554	-556	-549	-556	-566	-576	-597	-617	-562	-549	-687	-542	
Count Time	RSC30RSD61	150	159.8	0.02	0.4	0	9	9.8	-548	-550	-560	-568	-571	-567	-570	-558	-562	-560	-530	-545	
Count Time	RSC30RSD62	150	159.8	0.02	0.6	0	9	9.8	-551	-559	-559	-563	-551	-550	-543	-536	-552	-559	-605	-547	
Count Time	RSC30RSD63	150	159.8	0.02	0.8	0	9	9.8	-543	-550	-554	-559	-559	-559	-563	-576	-553	-554	-632	-541	
Count Time	RSC30RSD64	150	159.8	0.02	1	0	9	9.8	-534	-542	-549	-554	-550	-546	-547	-536	-545	-549	-487	-534	
Count Time	RSC30RSD65	150	159.8	0.02	1.2	0	9	9.8	-552	-560	-564	-562	-558	-561	-563	-574	-560	-564	-563	-550	
Count Time	RSC30RSD66	150	159.8	0.02	1.5	0	9	9.8	-547	-552	-554	-555	-556	-554	-552	-556	-553	-544	-536	-540	
Count Time	RSC30RSD67	150	159.8	0.02	1.75	0	9	9.8	-548	-550	-555	-560	-564	-565	-563	-551	-557	-555	-575	-541	
Count Time	RSC30RSD68	150	159.8	0.02	2	0	9	9.8	-541	-546	-550	-554	-555	-558	-564	-565	-554	-550	-520	-539	
Count Time	RSC30RSD69	150	159.8	0.02	3	0	9	9.8	-544	-553	-557	-563	-563	-564	-564	-546	-558	-557	-588	-542	

Investigation	Test ID	Test Settings							Sliding Gravity								Ave. Grav.	Gravity	Para	P-V Fit
		Start	Stop	Step	Time	Height	Psi	Range	Threshold											
		°2θ	°2θ	°2θ	s	mm	Tilts	°	10%	20%	30%	40%	50%	60%	70%	80%				
Range	RSC30RSD70	150	159.8	0.02	2	0	9	9.8	-538	-547	-553	-560	-561	-564	-558	-557	-554	-553	-551	-537
Range	RSC30RSD71	151	159.5	0.02	2	0	9	9.0	-535	-544	-549	-548	-555	-558	-563	-574	-549	-549	-570	-531
Range	RSC30RSD72	151	159	0.02	2	0	9	8.0	-509	-523	-528	-535	-542	-555	-569	-602	-533	-528	-576	-505
Range	RSC30RSD73	152	158	0.02	2	0	9	6.0	-462	-473	-479	-487	-494	-499	-504	-516	-485	-479	-506	-449
Range	RSC30RSD76	153	157.5	0.02	2	0	9	5.0	-431	-448	-462	-470	-476	-486	-503	-508	-456	-408	-549	-419
Range	RSC30RSD74	153	157	0.02	2	0	9	4.0	-395	-406	-418	-426	-430	-437	-445	-450	-424	-418	-425	-398

Table D2 Full numerical data for tests conducted on the heat-treated aluminium specimen.

Investigation	Test ID	Test Settings							Sliding Gravity								Ave. Grav.	Gravity	Para	P-V Fit
		Start	Stop	Step	Time	Height	Psi	Range	Threshold											
		°20	°20	°20	s	mm	Tilts	°	10%	20%	30%	40%	50%	60%	70%	80%				
Repeatability	RSB29RS1	152	158	0.02	2	0	9	6.0	-195	-196	-195	-196	-196	-195	-195	-194	-193	-196	-183	-197
Repeatability	RSB29RS2	152	158	0.02	2	0	9	6.0	-197	-198	-198	-198	-197	-197	-197	-198	-195	-198	-196	-198
Repeatability	RSB29RS3	152	158	0.02	2	0	9	6.0	-198	-198	-201	-201	-200	-199	-198	-195	-191	-201	-195	-199
Repeatability	RSB29RS4	152	158	0.02	2	0	9	6.0	-200	-201	-200	-199	-199	-200	-200	-200	-200	-199	-192	-200
Repeatability	RSB29RS5	152	158	0.02	2	0	9	6.0	-198	-200	-200	-200	-199	-199	-197	-196	-194	-199	-196	-200
Repeatability	RSB29RS6	152	158	0.02	2	0	9	6.0	-198	-196	-197	-196	-197	-197	-194	-203	-205	-196	-193	-198
Repeatability	RSB29RS7	152	158	0.02	2	0	9	6.0	-196	-196	-197	-196	-196	-198	-196	-195	-195	-196	-192	-196
Repeatability	RSB29RS8	152	158	0.02	2	0	9	6.0	-198	-199	-201	-199	-198	-198	-196	-197	-195	-199	-191	-199
Repeatability	RSB29RS9	152	158	0.02	2	0	9	6.0	-201	-199	-202	-202	-201	-200	-198	-199	-202	-202	-206	-201
Repeatability	RSB29RS10	152	158	0.02	2	0	9	6.0	-197	-200	-199	-198	-197	-195	-194	-195	-196	-198	-194	-199
Reproducibility	RSB29RS11	152	158	0.02	2	0	9	6.0	-205	-204	-204	-204	-204	-203	-205	-208	-208	-204	-197	-204
Reproducibility	RSB29RS12	152	158	0.02	2	0	9	6.0	-204	-203	-205	-205	-206	-206	-205	-202	-201	-205	-206	-205
Reproducibility	RSB29RS13	152	158	0.02	2	0	9	6.0	-200	-200	-200	-199	-199	-200	-202	-200	-199	-199	-201	-200
Reproducibility	RSB29RS14	152	158	0.02	2	0	9	6.0	-198	-203	-202	-200	-200	-201	-202	-204	-114	-200	-200	-202
Reproducibility	RSB29RS15	152	158	0.02	2	0	9	6.0	-202	-199	-202	-203	-203	-203	-204	-202	-201	-203	-202	-203
Reproducibility	RSB29RS16	152	158	0.02	2	0	9	6.0	-202	-202	-204	-205	-203	-201	-201	-204	-191	-205	-200	-203
Reproducibility	RSB29RS17	152	158	0.02	2	0	9	6.0	-200	-200	-200	-200	-200	-200	-199	-198	-200	-200	-194	-200
Reproducibility	RSB29RS18	152	158	0.02	2	0	9	6.0	-202	-204	-204	-203	-202	-202	-203	-201	-201	-203	-203	-204
Reproducibility	RSB29RS19	152	158	0.02	2	0	9	6.0	-206	-203	-206	-207	-206	-204	-206	-210	-209	-207	-205	-205
Reproducibility	RSB29RS20	152	158	0.02	2	0	9	6.0	-205	-203	-205	-205	-205	-205	-207	-207	-194	-205	-200	-206
Height	RSB29RS21	152	158	0.02	2	0.02	9	6.0	-203	-204	-206	-206	-205	-204	-203	-202	-199	-206	-195	-205
Height	RSB29RS22	152	158	0.02	2	0.1	9	6.0	-204	-203	-204	-205	-206	-205	-204	-202	-205	-205	-201	-205
Height	RSB29RS23	152	158	0.02	2	0.2	9	6.0	-214	-209	-212	-211	-212	-214	-217	-219	-219	-211	-218	-212
Height	RSB29RS24	152	158	0.02	2	0.5	9	6.0	-213	-214	-213	-213	-211	-212	-213	-213	-214	-213	-211	-213
Height	RSB29RS25	152	158	0.02	2	1	9	6.0	-211	-207	-210	-210	-211	-211	-211	-211	-214	-210	-215	-213
Height	RSB29RS26	152	158	0.02	2	0	9	6.0	-210	-211	-211	-211	-211	-211	-210	-210	-210	-211	-210	-211
Height	RSB29RS27	152	158	0.02	2	-0.5	9	6.0	-205	-202	-204	-204	-204	-205	-207	-207	-209	-204	-204	-204
Height	RSB29RS28	152	158	0.02	2	-1	9	6.0												
Height	RSB29RS29	152	158	0.02	2	-0.2	9	6.0												
Height	RSB29RS30	152	158	0.02	2	-0.02	9	6.0												

Tests Not Conducted

Investigation	Test ID	Test Settings							Sliding Gravity								Ave. Grav.	Gravity	Para	P-V Fit			
		Start	Stop	Step	Time	Height	Psi	Range	Threshold														
		°20	°20	°20	s	mm	Tilts	°	10%	20%	30%	40%	50%	60%	70%	80%					NA	30%	80%
Height	RSB29RS31	152	158	0.02	2	0	9	6.0	Test Not Conducted														
Height	RSB29RS32	152	158	0.02	2	1	9	6.0	-214	-209	-212	-211	-212	-214	-217	-219	-219	-211	-218	-212			
Height	RSB29RS33	152	158	0.02	2	1	9	6.0	-217	-209	-217	-219	-219	-220	-219	-219	-217	-219	-212	-218			
Height	RSB29RS34	152	158	0.02	2	1	9	6.0	-213	-214	-214	-213	-214	-212	-212	-212	-194	-213	-214	-215			
Height	RSB29RS35	152	158	0.02	2	1	9	6.0	-214	-210	-216	-216	-218	-216	-214	-213	-212	-216	-197	-216			
Height	RSB29RS36	152	158	0.02	2	1	9	6.0	-217	-216	-217	-216	-215	-216	-217	-219	-221	-216	-214	-217			
Height	RSB29RS37	152	158	0.02	2	1	9	6.0	-214	-210	-214	-216	-216	-215	-214	-214	-212	-216	-223	-216			
Height	RSB29RS38	152	158	0.02	2	1	9	6.0	-215	-215	-214	-214	-214	-214	-216	-215	-218	-214	-222	-215			
Height	RSB29RS39	152	158	0.02	2	1	9	6.0	-213	-217	-213	-213	-213	-215	-216	-195	-197	-213	-232	-214			
Height	RSB29RS40	152	158	0.02	2	1	9	6.0	-214	-212	-215	-215	-215	-216	-216	-213	-212	-215	-220	-215			
Height	RSB29RS41	152	158	0.02	2	1	9	6.0	-217	-210	-218	-219	-219	-218	-218	-218	-217	-219	-216	-218			
Step Size	RSB29RS42	152	158	0.01	2	0	9	6.0	-206	-205	-205	-206	-206	-206	-207	-207	-208	-207	-208	-205			
Step Size	RSB29RS43	152	158	0.03	2	0	9	6.0	-204	-201	-204	-206	-206	-207	-205	-202	-204	-206	-202	-205			
Step Size	RSB29RS44	152	158	0.04	2	0	9	6.0	-200	-197	-201	-203	-202	-201	-199	-198	-195	-203	-194	-201			
Step Size	RSB29RS45	152	158	0.05	2	0	9	6.0	-208	-204	-207	-206	-207	-208	-209	-210	-211	-206	-207	-207			
Step Size	RSB29RS46	152	158	0.06	2	0	9	6.0	-208	-200	-209	-208	-209	-208	-210	-211	-212	-208	-204	-207			
Step Size	RSB29RS47	152	158	0.07	2	0	9	6.0	-208	-204	-205	-207	-207	-209	-211	-211	-214	-207	-202	-208			
Step Size	RSB29RS48	152	158	0.08	2	0	9	6.0	-201	-199	-201	-203	-201	-201	-200	-201	-203	-203	-207	-202			
Step Size	RSB29RS49	152	158	0.09	2	0	9	6.0	-204	-196	-204	-205	-207	-208	-207	-204	-201	-205	-196	-206			
Step Size	RSB29RS50	152	158	0.1	2	0	9	6.0	-208	-201	-204	-207	-207	-209	-211	-213	-215	-207	-198	-209			
Step Size	RSB29RS51	152	158	0.02	2	0	9	6.0	-207	-203	-206	-206	-206	-208	-207	-206	-210	-205	-201	-207			
Psi Tilts	RSB29RS52	152	158	0.02	2	0	21	6.0	-208	-205	-207	-207	-207	-207	-209	-211	-213	-207	-212	-207			
Psi Tilts	RSB29RS53	152	158	0.02	2	0	17	6.0	-207	-203	-207	-208	-208	-208	-207	-208	-210	-208	-202	-207			
Psi Tilts	RSB29RS54	152	158	0.02	2	0	15	6.0	-209	-208	-209	-208	-208	-208	-210	-212	-213	-208	-210	-209			
Psi Tilts	RSB29RS55	152	158	0.02	2	0	13	6.0	-206	-207	-207	-207	-206	-206	-207	-205	-206	-207	-210	-207			
Psi Tilts	RSB29RS56	152	158	0.02	2	0	11	6.0	-209	-209	-209	-209	-209	-209	-208	-209	-211	-209	-211	-209			
Psi Tilts	RSB29RS57	152	158	0.02	2	0	9	6.0	-207	-206	-205	-204	-205	-206	-206	-210	-214	-204	-217	-206			
Psi Tilts	RSB29RS58	152	158	0.02	2	0	7	6.0	-205	-200	-205	-206	-206	-205	-205	-206	-204	-206	-198	-204			
Psi Tilts	RSB29RS59	152	158	0.02	2	0	5	6.0	-203	-201	-205	-205	-204	-201	-202	-203	-205	-205	-230	-204			
Count Time	RSB29RS60	152	158	0.02	0.2	0	9	6.0	-211	-217	-220	-217	-212	-210	-208	-204	-200	-217	-279	-213			
Count Time	RSB29RS61	152	158	0.02	0.4	0	9	6.0	-208	-200	-206	-204	-204	-209	-213	-213	-211	-204	-204	-206			
Count Time	RSB29RS62	152	158	0.02	0.6	0	9	6.0	-203	-199	-204	-204	-204	-203	-202	-201	-204	-204	-214	-204			

Investigation	Test ID	Test Settings							Sliding Gravity								Ave. Grav.	Gravity	Para	P-V Fit
		Start	Stop	Step	Time	Height	Psi	Range	Threshold											
		°2θ	°2θ	°2θ	s	mm	Tilts	°	10%	20%	30%	40%	50%	60%	70%	80%				
Count Time	RSB29RS63	152	158	0.02	0.8	0	9	6.0	-209	-204	-210	-210	-210	-209	-208	-208	-209	-210	-223	-210
Count Time	RSB29RS64	152	158	0.02	1	0	9	6.0	-205	-200	-204	-206	-205	-205	-206	-204	-206	-206	-181	-205
Count Time	RSB29RS65	152	158	0.02	1.2	0	9	6.0	-206	-204	-206	-206	-206	-205	-206	-209	-208	-206	-212	-207
Count Time	RSB29RS66	152	158	0.02	1.5	0	9	6.0	-203	-203	-203	-203	-203	-204	-203	-203	-202	-203	-208	-205
Count Time	RSB29RS67	152	158	0.02	1.75	0	9	6.0	-204	-201	-205	-206	-206	-205	-203	-202	-203	-206	-199	-205
Count Time	RSB29RS68	152	158	0.02	2	0	9	6.0	-205	-202	-204	-204	-205	-205	-206	-208	-209	-204	-202	-205
Count Time	RSB29RS69	152	158	0.02	3	0	9	6.0	-203	-203	-205	-205	-205	-204	-203	-202	-202	-205	-204	-204
Range	RSB29RS70	150	160	0.02	2	0	9	10.0	-205	-201	-204	-204	-205	-204	-206	-207	-210	-204	-218	-203
Range	RSB29RS71	150.5	159.5	0.02	2	0	9	9.0	-205	-204	-205	-206	-206	-205	-205	-205	-206	-206	-203	-205
Range	RSB29RS72	151	159	0.02	2	0	9	8.0	-205	-203	-203	-204	-205	-206	-206	-206	-205	-204	-208	-204
Range	RSB29RS73	152	158	0.02	2	0	9	6.0	-206	-199	-204	-206	-205	-205	-207	-209	-212	-206	-209	-205
Range	RSB29RS74	152.5	157.5	0.02	2	0	9	5.0	-201	-200	-202	-203	-201	-200	-200	-201	-204	-203	-194	-202
Range	RSB29RS75	153	157	0.02	2	0	9	4.0	-202	-199	-202	-204	-204	-205	-204	-202	-200	-204	-194	-199
Range	RSB29RS76	153.5	156.5	0.02	2	0	9	3.0	-198	-192	-195	-197	-197	-198	-200	-202	-203	-197	-208	-189
Range	RSB29RS77	154	156	0.02	2	0	9	2.0	-196	-192	-193	-194	-194	-195	-196	-199	-201	-194	-210	-215

Table D3 Full numerical data for tests conducted on the ground titanium specimen.

Investigation	Test ID	Test Settings							Sliding Gravity								Ave. Grav.	Gravity	Para	P-V Fit
		Start	Stop	Step	Time	Height	Psi	Range	Threshold											
		°2θ	°2θ	°2θ	s	mm	Tilts	°	10%	20%	30%	40%	50%	60%	70%	80%				
Repeatability	T12 RS1	136	146	0.02	10	0	9	10.0	-421	-448	-436	-423	-411	-402	-397	-385	-369	-423	-397	-434
Repeatability	T12 RS2	136	146	0.02	10	0	9	10.0	-440	-468	-450	-440	-428	-420	-418	-423	-430	-440	-456	-445
Repeatability	T12 RS3	136	146	0.02	10	0	9	10.0	-412	-442	-435	-419	-402	-393	-386	-380	-385	-419	-468	-427
Repeatability	T12 RS4	136	146	0.02	10	0	9	10.0	-420	-451	-439	-427	-410	-399	-398	-391	-387	-427	-367	-434
Repeatability	T12 RS5	136	146	0.02	10	0	9	10.0	-403	-437	-438	-417	-398	-384	-371	-352	-345	-417	-362	-429
Repeatability	T12 RS6	136	146	0.02	10	0	9	10.0	-409	-426	-417	-413	-407	-403	-394	-389	-355	-413	-419	-431
Repeatability	T12 RS7	136	146	0.02	10	0	9	10.0	-417	-439	-436	-422	-409	-400	-390	-380	-390	-422	-397	-429
Repeatability	T12 RS8	136	146	0.02	10	0	9	10.0	-423	-442	-442	-434	-418	-408	-398	-390	-385	-434	-396	-431
Repeatability	T12 RS9	136	146	0.02	10	0	9	10.0	-408	-444	-434	-425	-406	-387	-381	-366	-354	-425	-352	-432
Repeatability	T12 RS10	136	146	0.02	10	0	9	10.0	-424	-455	-447	-431	-417	-396	-383	-374	-359	-431	-316	-434
Reproducibility	T12 RS11	136	146	0.02	10	0	9	10.0	-420	-448	-437	-423	-408	-400	-391	-380	-370	-423	-367	-422
Reproducibility	T12 RS12	136	146	0.02	10	0	9	10.0	-396	-452	-431	-408	-389	-374	-360	-349	-343	-408	-289	-417
Reproducibility	T12 RS13	136	146	0.02	10	0	9	10.0	-412	-443	-430	-419	-412	-406	-394	-375	-367	-419	-389	-432
Reproducibility	T12 RS14	136	146	0.02	10	0	9	10.0	-441	-441	-444	-446	-442	-433	-425	-441	-459	-446	-328	-444
Reproducibility	T12 RS15	136	146	0.02	10	0	9	10.0	-422	-446	-432	-425	-417	-409	-408	-412	-412	-425	-341	-429
Reproducibility	T12 RS16	136	146	0.02	10	0	9	10.0	-412	-439	-429	-417	-406	-398	-393	-379	-350	-417	-396	-421
Reproducibility	T12 RS17	136	146	0.02	10	0	9	10.0	-391	-431	-414	-400	-392	-382	-374	-369	-354	-400	-270	-411
Reproducibility	T12 RS18	136	146	0.02	10	0	9	10.0	-404	-430	-420	-409	-400	-392	-381	-374	-370	-409	-374	-413
Reproducibility	T12 RS19	136	146	0.02	10	0	9	10.0	-422	-448	-431	-425	-422	-417	-402	-402	-398	-425	-484	-438
Reproducibility	T12 RS20	136	146	0.02	10	0	9	10.0	-379	-422	-408	-389	-381	-365	-349	-339	-327	-389	-432	-401
Height	T12 RS21	136	146	0.02	10	-0.02	9	10.0	-413	-451	-434	-423	-415	-400	-382	-353	-136	-423	-307	-425
Height	T12 RS22	136	146	0.02	10	0.1	9	10.0	-416	-441	-420	-412	-404	-402	-399	-410	-421	-412	-476	-422
Height	T12 RS23	136	146	0.02	10	0.2	9	10.0	-426	-453	-443	-432	-420	-410	-404	-401	-404	-432	-515	-443
Height	T12 RS24	136	146	0.02	10	0.5	9	10.0	-411	-445	-434	-423	-413	-397	-387	-378	-361	-423	-381	-431
Height	T12 RS25	136	146	0.02	10	1	9	10.0	-430	-443	-441	-431	-419	-417	-417	-420	-447	-431	-141	-437
Height	T12 RS26	136	146	0.02	10	0	9	10.0	-432	-449	-446	-440	-424	-407	-400	-396	-397	-440	-306	-435
Height	T12 RS27	136	146	0.02	10	-0.5	9	10.0	-409	-432	-433	-425	-408	-396	-386	-371	-367	-425	-171	-423
Height	T12 RS28	136	146	0.02	10	-1	9	10.0	-412	-439	-419	-407	-406	-397	-396	-391	-392	-407	-347	-428
Height	T12 RS29	136	146	0.02	10	-0.2	9	10.0	-403	-447	-438	-418	-394	-373	-369	-367	-374	-418	-348	-425
Height	T12 RS30	136	146	0.02	10	0.02	9	10.0	-413	-441	-437	-423	-413	-405	-393	-388	-363	-423	-388	-425
Height	T12 RS31	136	146	0.02	10	0	9	10.0	-407	-448	-444	-425	-402	-392	-373	-351	-338	-425	-394	-423

Investigation	Test ID	Test Settings							Sliding Gravity								Ave. Grav.	Gravity	Para	P-V Fit
		Start	Stop	Step	Time	Height	Psi	Range	Threshold											
		°2θ	°2θ	°2θ	s	mm	Tilts	°	10%	20%	30%	40%	50%	60%	70%	80%				
Height	T12 RS32	136	146	0.02	10	1	9	10.0	-422	-448	-435	-423	-414	-409	-412	-412	-413	-423	-479	-436
Height	T12 RS33	136	146	0.02	10	1	9	10.0	-431	-456	-453	-435	-425	-408	-400	-402	-382	-435	-376	-436
Height	T12 RS34	136	146	0.02	10	1	9	10.0	-440	-462	-458	-446	-426	-411	-404	-406	-407	-446	-384	-441
Height	T12 RS35	136	146	0.02	10	1	9	10.0	-429	-452	-449	-434	-428	-415	-404	-397	-403	-434	-404	-430
Height	T12 RS36	136	146	0.02	10	1	9	10.0	-424	-444	-432	-424	-420	-413	-412	-417	-417	-424	-341	-435
Height	T12 RS37	136	146	0.02	10	1	9	10.0	-422	-447	-440	-428	-422	-403	-381	-378	-390	-428	-321	-429
Height	T12 RS38	136	146	0.02	10	1	9	10.0	Tests Not Conducted											
Height	T12 RS39	136	146	0.02	10	1	9	10.0												
Height	T12 RS40	136	146	0.02	10	1	9	10.0												
Height	T12 RS41	136	146	0.02	10	1	9	10.0												
Step Size	T12 RS42	136	146	0.01	10	0	9	10.0	-411	-435	-428	-419	-407	-398	-392	-388	-388	-419	-326	-424
Step Size	T12 RS43	136	146	0.03	10	0	9	10.0	-410	-462	-435	-416	-405	-394	-382	-384	-385	-416	-366	-428
Step Size	T12 RS44	136	146	0.04	10	0	9	10.0	-421	-450	-439	-421	-412	-412	-395	-387	-392	-421	-214	-435
Step Size	T12 RS45	136	146	0.05	10	0	9	10.0	-428	-445	-444	-425	-414	-411	-403	-419	-432	-425	-397	-427
Step Size	T12 RS46	136	146	0.06	10	0	9	10.0	-426	-457	-460	-441	-428	-399	-376	-356	-363	-441	-379	-445
Step Size	T12 RS47	136	146	0.07	10	0	9	10.0	-419	-453	-453	-420	-417	-403	-393	-394	-387	-420	-361	-433
Step Size	T12 RS48	136	146	0.08	10	0	9	10.0	-416	-435	-431	-435	-419	-402	-396	-377	-377	-435	-419	-436
Step Size	T12 RS49	136	146	0.09	10	0	9	10.0	-432	-456	-443	-440	-420	-407	-405	-403	-417	-440	-437	-438
Step Size	T12 RS50	136	146	0.1	10	0	9	10.0	-398	-421	-410	-400	-380	-372	-385	-393	-419	-400	-502	-420
Psi Tilts	T12 RS52	136	146	0.02	10	0	21	10.0	-417	-443	-439	-429	-414	-407	-399	-390	-380	-429	-347	-434
Psi Tilts	T12 RS53	136	146	0.02	10	0	17	10.0	Test Not Conducted											
Psi Tilts	T12 RS54	136	146	0.02	10	0	15	10.0												
Psi Tilts	T12 RS55	136	146	0.02	10	0	13	10.0	-427	-459	-449	-433	-419	-410	-404	-402	-396	-433	-360	-441
Psi Tilts	T12 RS56	136	146	0.02	10	0	11	10.0	-413	-439	-444	-436	-418	-403	-390	-381	-362	-436	-422	-434
Psi Tilts	T12 RS58	136	146	0.02	10	0	7	10.0	-415	-440	-438	-419	-404	-389	-376	-370	-377	-419	-402	-423
Psi Tilts	T12 RS59	136	146	0.02	10	0	5	10.0	-417	-442	-432	-423	-412	-403	-394	-384	-367	-423	-386	-427
Psi Tilts	T12 RS59	136	146	0.02	10	0	5	10.0	-420	-438	-439	-427	-416	-417	-407	-402	-396	-427	-540	-438
Count Time	T12 RS60	136	146	0.02	0.2	0	9	10.0	-466	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Count Time	T12 RS61	136	146	0.02	0.4	0	9	10.0	-430	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Count Time	T12 RS62	136	146	0.02	0.6	0	9	10.0	-375	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Count Time	T12 RS63	136	146	0.02	0.8	0	9	10.0	-449	-443	-469	-464	-452	-455	-442	-406	-359	-464	NA	-449
Count Time	T12 RS64	136	146	0.02	1	0	9	10.0	-427	-431	-435	-419	-415	-411	-429	-450	-432	-419	NA	-431
Count Time	T12 RS65	136	146	0.02	1.2	0	9	10.0	-416	-463	-439	-408	-387	-385	-391	-453	-398	-408	NA	-409

Investigation	Test ID	Test Settings							Sliding Gravity								Ave. Grav.	Gravity	Para	P-V Fit
		Start	Stop	Step	Time	Height	Psi	Range	Threshold											
		°2θ	°2θ	°2θ	s	mm	Tilts	°	10%	20%	30%	40%	50%	60%	70%	80%				
Count Time	T12 RS66	136	146	0.02	1.5	0	9	10.0	-419	-442	-442	-430	-412	-406	-405	-408	-412	-431	-153	-434
Count Time	T12 RS67	136	146	0.02	1.75	0	9	10.0	-430	-432	-443	-435	-422	-416	-419	-419	-426	-435	-563	-435
Count Time	T12 RS68	136	146	0.02	2	0	9	10.0	-397	-397	-416	-413	-403	-392	-379	-366	-341	-413	-141	-428
Count Time	T12 RS69	136	146	0.02	3	0	9	10.0	-429	-478	-445	-430	-416	-423	-417	-397	-370	-430	-278	-435
Range	T12 RS70	138	145	0.02	10	0	9	7.0	-406	-414	-414	-408	-402	-397	-396	-401	-417	-408	-489	-412
Range	T12 RS71	139	144	0.02	10	0	9	5.0	-385	-390	-396	-391	-380	-378	-381	-382	-364	-391	-375	-395
Range	T12 RS72	140	143	0.02	10	0	9	3.0	-326	-274	-303	-322	-341	-346	-351	-351	-341	-322	-279	-227

Table D4 Full numerical data for tests conducted on the cold expanded hole specimen, using both +ve and -ve Psi tilt data.

Distance from hole, mm	Test ID	Test Settings							Sliding Gravity								Ave. Grav.	Gravity	Para	P-V Fit
		Start	Stop	Step	Time	Height	Psi	Range	Threshold											
		°20	°20	°20	s	mm	Tilts	°	10%	20%	30%	40%	50%	60%	70%	80%				
1	CEH RS6	151	161	0.02	2	9	0	10.0	-218	-210	-212	-221	-229	-233	-221	-183	-191	-221	-255	-218
1	CEH RS7	151	161	0.02	2	9	0.02	10.0	-228	-205	-214	-224	-227	-235	-239	-247	-255	-224	-253	-220
1	CEH RS8	151	161	0.02	2	9	0.1	10.0	-224	-213	-215	-221	-225	-227	-231	-233	-240	-221	-229	-219
1	CEH RS9	151	161	0.02	2	9	0.2	10.0	-225	-196	-210	-218	-222	-228	-235	-239	-243	-223	-269	-213
1	CEH RS10	151	161	0.02	2	9	0.5	10.0	-223	-210	-214	-217	-219	-224	-230	-234	-238	-217	-215	-216
1	CEH RS11	151	161	0.02	2	9	1.2	10.0	-236	-231	-225	-230	-234	-239	-239	-245	-250	-232	-243	-230
1	CEH RS12	151	161	0.02	2	9	0	10.0	-235	-217	-222	-230	-236	-238	-243	-248	-252	-230	-262	-228
1	CEH RS13	151	161	0.02	2	9	-0.02	10.0	-228	-218	-221	-226	-229	-233	-237	-240	-241	-226	-244	-225
1	CEH RS14	151	161	0.02	2	9	-0.1	10.0	-226	-204	-213	-221	-226	-231	-236	-243	-249	-231	-256	-217
1	CEH RS15	151	161	0.02	2	9	-0.2	10.0	-231	-209	-224	-227	-232	-239	-243	-245	-246	-227	-250	-225
1	CEH RS16	151	161	0.02	2	9	-0.5	10.0	-229	-213	-222	-230	-232	-234	-241	-248	-251	-230	-218	-225
1	CEH RS17	151	161	0.02	2	9	-1	10.0	-225	-204	-217	-221	-227	-229	-232	-233	-234	-221	-235	-216
1	CEH RS18	151	161	0.02	2	9	0	10.0	-229	-211	-222	-229	-236	-238	-244	-249	-254	-229	-220	-229
1	CEH RS19	151	161	0.02	2	9	1	10.0	-227	-217	-218	-223	-229	-231	-232	-234	-242	-223	-260	-222
1	CEH RS20	151	161	0.02	2	9	1	10.0	-229	-203	-216	-223	-229	-233	-238	-242	-241	-221	-244	-221
1	CEH RS21	151	161	0.02	2	9	1	10.0	-228	-202	-211	-219	-224	-230	-237	-239	-240	-216	-216	-217
1	CEH RS22	151	161	0.02	2	9	1	10.0	-224	-219	-218	-220	-224	-228	-229	-230	-234	-218	-247	-220
1	CEH RS23	151	161	0.02	2	9	1	10.0	-226	-210	-214	-220	-225	-231	-238	-239	-240	-225	-219	-219
1	CEH RS24	151	161	0.02	2	9	1	10.0	-236	-216	-222	-231	-237	-241	-240	-242	-244	-231	-255	-227
1	CEH RS25	151	161	0.02	2	9	1.2	10.0	-241	-219	-221	-231	-240	-248	-252	-257	-267	-232	-235	-229
1	CEH RS26	151	161	0.02	2	9	1.2	10.0	-234	-218	-224	-230	-235	-240	-242	-243	-236	-230	-210	-229
1	CEH RS27	151	161	0.02	2	9	1.2	10.0	-235	-232	-225	-227	-232	-237	-242	-244	-241	-226	-265	-227
1	CEH RS28	151	161	0.02	2	9	1.2	10.0	-237	-210	-220	-229	-234	-239	-242	-245	-250	-229	-262	-226
1	CEH RS29	151	161	0.02	2	9	0	10.0	-231	-218	-222	-227	-230	-234	-236	-240	-249	-219	-246	-225
1	CEH RS30	151	161	0.02	2	9	1	10.0	-244	-226	-234	-242	-249	-251	-253	-254	-261	-242	-239	-239
1	CEH RS31	151	161	0.02	2	9	1	10.0	-254	-228	-241	-247	-254	-259	-264	-269	-272	-247	-237	-244
1	CEH RS32	151	161	0.02	2	9	1	10.0	-249	-229	-238	-244	-247	-253	-256	-262	-261	-244	-257	-239
1	CEH RS33	151	161	0.02	2	9	1	10.0	-242	-222	-230	-238	-243	-249	-253	-257	-257	-238	-249	-235
1	CEH RS34	151	161	0.02	2	9	1	10.0	-242	-211	-225	-238	-247	-251	-256	-261	-268	-238	-274	-231
1	CEH RS35	151	161	0.02	2	9	0	10.0	-227	-212	-220	-225	-229	-234	-238	-241	-252	-225	-253	-223

Distance from hole, mm	Test ID	Test Settings							Sliding Gravity								Ave. Grav.	Gravity	Para	P-V Fit
		Start	Stop	Step	Time	Height	Psi	Range	Threshold											
		°2θ	°2θ	°2θ	s	mm	Tilts	°	10%	20%	30%	40%	50%	60%	70%	80%				
1	CEH RS36	151	161	0.02	2	9	0	10.0	-233	-224	-225	-227	-230	-235	-236	-243	-249	-227	-245	-228
1	CEH RS37	151	161	0.02	2	9	0	10.0	-226	-207	-215	-222	-226	-229	-234	-236	-241	-218	-266	-218
1	CEH RS38	151	161	0.02	2	9	0	10.0	-229	-213	-219	-226	-231	-232	-236	-242	-249	-226	-267	-221
1	CEH RS39	151	161	0.02	2	9	0	10.0	-230	-204	-215	-224	-234	-238	-239	-247	-256	-224	-258	-224
1	CEH RS40	151	161	0.02	2	9	0	10.0	-230	-214	-217	-224	-229	-233	-240	-246	-250	-222	-252	-222
1	CEH RS41	151	161	0.02	2	9	0	10.0	-239	-218	-219	-227	-235	-241	-247	-253	-260	-232	-255	-227
1	CEH RS42	151	161	0.02	2	9	0	10.0	-236	-209	-219	-227	-232	-237	-241	-251	-262	-227	-264	-224
1	CEH RS43	151	161	0.02	2	9	0	10.0	-231	-215	-221	-227	-234	-241	-245	-250	-249	-224	-252	-224
1	CEH RS44	151	161	0.02	2	9	0	10.0	-241	-218	-228	-236	-239	-244	-250	-254	-257	-233	-262	-231

Table D5 Full numerical data for tests conducted on the cold expanded hole specimen, using just +ve Psi tilt data.

Distance from hole, mm	Test ID	Test Settings							Sliding Gravity								Ave. Grav.	Gravity	Para	P-V Fit
		Start	Stop	Step	Time	Height	Psi	Range	Threshold											
		°20	°20	°20	s	mm	Tilts	°	10%	20%	30%	40%	50%	60%	70%	80%				
1	CEH RS6	151	161	0.02	2	5	0	10.0	-184	-171	-177	-184	-187	-191	-190	-187	-188	-178	-227	-181
1	CEH RS7	151	161	0.02	2	5	0.02	10.0	-176	-154	-173	-176	-178	-181	-184	-186	-181	-172	-130	-173
1	CEH RS8	151	161	0.02	2	5	0.1	10.0	-222	-218	-213	-218	-220	-221	-226	-229	-236	-218	-219	-216
1	CEH RS9	151	161	0.02	2	5	0.2	10.0	-223	-185	-208	-215	-219	-227	-236	-243	-257	-229	-306	-209
1	CEH RS10	151	161	0.02	2	5	0.5	10.0	-231	-219	-221	-223	-225	-231	-238	-246	-252	-223	-227	-220
1	CEH RS11	151	161	0.02	2	5	1.2	10.0	-251	-259	-244	-241	-244	-251	-252	-256	-264	-245	-278	-243
1	CEH RS12	151	161	0.02	2	5	0	10.0	-192	-181	-179	-184	-186	-193	-199	-205	-217	-184	-169	-189
1	CEH RS13	151	161	0.02	2	5	-0.02	10.0	-190	-196	-185	-184	-188	-191	-192	-196	-189	-184	-179	-184
1	CEH RS14	151	161	0.02	2	5	-0.1	10.0	-173	-161	-165	-167	-173	-179	-184	-182	-182	-167	-172	-168
1	CEH RS15	151	161	0.02	2	5	-0.2	10.0	-157	-145	-161	-160	-158	-162	-159	-157	-152	-160	-159	-161
1	CEH RS16	151	161	0.02	2	5	-0.5	10.0	-151	-165	-149	-147	-146	-147	-148	-147	-148	-136	-187	-152
1	CEH RS17	151	161	0.02	2	5	-1	10.0	-118	-75	-101	-122	-128	-128	-127	-125	-126	-122	-195	-123
1	CEH RS18	151	161	0.02	2	5	0	10.0	-180	-181	-179	-180	-179	-177	-180	-181	-179	-180	-153	-182
1	CEH RS19	151	161	0.02	2	5	1	10.0	-243	-235	-233	-238	-241	-244	-246	-252	-259	-238	-345	-234
1	CEH RS20	151	161	0.02	2	5	1	10.0	-247	-204	-228	-238	-248	-257	-264	-272	-274	-238	-271	-234
1	CEH RS21	151	161	0.02	2	5	1	10.0	-245	-205	-223	-234	-244	-254	-265	-270	-271	-234	-204	-230
1	CEH RS22	151	161	0.02	2	5	1	10.0	-238	-233	-227	-232	-235	-240	-243	-244	-254	-232	-258	-230
1	CEH RS23	151	161	0.02	2	5	1	10.0	-239	-227	-224	-228	-234	-243	-254	-257	-251	-239	-210	-231
1	CEH RS24	151	161	0.02	2	5	1	10.0	-228	-204	-216	-222	-227	-230	-235	-243	-252	-229	-303	-225
1	CEH RS25	151	161	0.02	2	5	1.2	10.0	-266	-239	-238	-247	-260	-271	-280	-291	-305	-247	-275	-247
1	CEH RS26	151	161	0.02	2	5	1.2	10.0	-247	-237	-239	-244	-247	-253	-256	-257	-244	-244	-230	-244
1	CEH RS27	151	161	0.02	2	5	1.2	10.0	-247	-258	-239	-236	-240	-247	-251	-252	-250	-236	-293	-238
1	CEH RS28	151	161	0.02	2	5	1.2	10.0	-247	-213	-227	-240	-247	-254	-263	-265	-264	-240	-271	-233
1	CEH RS29	151	161	0.02	2	5	0	10.0	-180	-170	-171	-175	-178	-182	-184	-191	-196	-175	-256	-175
1	CEH RS30	151	161	0.02	2	5	1	10.0	-239	-228	-233	-234	-237	-244	-248	-247	-245	-234	-185	-240
1	CEH RS31	151	161	0.02	2	5	1	10.0	-251	-222	-236	-242	-249	-259	-262	-271	-279	-242	-288	-242
1	CEH RS32	151	161	0.02	2	5	1	10.0	-251	-217	-236	-243	-244	-251	-258	-276	-285	-243	-342	-237
1	CEH RS33	151	161	0.02	2	5	1	10.0	-250	-249	-238	-237	-243	-250	-257	-264	-267	-237	-258	-236
1	CEH RS34	151	161	0.02	2	5	1	10.0	-259	-220	-237	-248	-258	-266	-276	-286	-295	-248	-305	-243
1	CEH RS35	151	161	0.02	2	5	0	10.0	-190	-199	-188	-187	-187	-190	-191	-188	-189	-187	-254	-187
1	CEH RS36	151	161	0.02	2	5	0	10.0	-185	-172	-175	-176	-183	-191	-196	-197	-192	-176	-219	-181

Distance from hole, mm	Test ID	Test Settings							Sliding Gravity								Ave. Grav.	Gravity	Para	P-V Fit
		Start	Stop	Step	Time	Height	Psi	Range	Threshold											
		°2θ	°2θ	°2θ	s	mm	Tilts	°	10%	20%	30%	40%	50%	60%	70%	80%				
1	CEH RS37	151	161	0.02	2	5	0	10.0	-185	-174	-176	-181	-183	-186	-195	-194	-197	-181	-252	-176
1	CEH RS38	151	161	0.02	2	5	0	10.0	-187	-169	-182	-186	-185	-185	-194	-199	-203	-184	-278	-185
1	CEH RS39	151	161	0.02	2	5	0	10.0	-181	-162	-179	-179	-180	-184	-187	-192	-196	-179	-291	-180
1	CEH RS40	151	161	0.02	2	5	0	10.0	-189	-178	-178	-181	-185	-191	-198	-205	-205	-181	-155	-183
1	CEH RS41	151	161	0.02	2	5	0	10.0	-190	-163	-178	-183	-188	-193	-198	-205	-211	-183	-254	-184
1	CEH RS42	151	161	0.02	2	5	0	10.0	-193	-149	-182	-189	-192	-202	-207	-207	-208	-189	-209	-183
1	CEH RS43	151	161	0.02	2	5	0	10.0	-190	-199	-187	-186	-191	-192	-192	-192	-182	-186	-174	-187
1	CEH RS44	151	161	0.02	2	5	0	10.0	-186	-167	-177	-178	-182	-191	-197	-200	-198	-138	-239	-181

Table D6 Full numerical data for tests conducted on the cold expanded hole specimen, using just -ve Psi tilt data.

Distance from hole, mm	Test ID	Test Settings							Sliding Gravity								Ave. Grav.	Gravity	Para	P-V Fit
		Start	Stop	Step	Time	Height	Psi	Range	Threshold											
		°2θ	°2θ	°2θ	s	mm	Tilts	°	10%	20%	30%	40%	50%	60%	70%	80%				
1	CEH RS6	151	161	0.02	2	5	0	10.0	-195	-184	-182	-191	-200	-200	-202	-203	-206	-191	-264	-197
1	CEH RS7	151	161	0.02	2	5	0.02	10.0	-193	-179	-190	-194	-195	-195	-195	-200	-202	-192	-168	-196
1	CEH RS8	151	161	0.02	2	5	0.1	10.0	-223	-217	-217	-220	-223	-225	-226	-228	-232	-220	-195	-220
1	CEH RS9	151	161	0.02	2	5	0.2	10.0	-226	-196	-215	-224	-226	-233	-240	-242	-242	-233	-274	-219
1	CEH RS10	151	161	0.02	2	5	0.5	10.0	-219	-205	-208	-210	-214	-221	-228	-234	-238	-210	-206	-212
1	CEH RS11	151	161	0.02	2	5	1.2	10.0	-217	-222	-210	-214	-214	-217	-218	-221	-220	-216	-232	-214
1	CEH RS12	151	161	0.02	2	5	0	10.0	-211	-199	-198	-207	-213	-215	-220	-222	-223	-207	-221	-213
1	CEH RS13	151	161	0.02	2	5	-0.02	10.0	-207	-214	-203	-204	-205	-209	-209	-205	-204	-204	-214	-208
1	CEH RS14	151	161	0.02	2	5	-0.1	10.0	-201	-189	-195	-199	-202	-205	-205	-207	-212	-213	-226	-197
1	CEH RS15	151	161	0.02	2	5	-0.2	10.0	-202	-192	-206	-208	-206	-207	-204	-197	-189	-208	-208	-204
1	CEH RS16	151	161	0.02	2	5	-0.5	10.0	-199	-210	-198	-197	-199	-194	-194	-195	-196	-189	-233	-200
1	CEH RS17	151	161	0.02	2	5	-1	10.0	-201	-172	-189	-203	-210	-212	-210	-203	-201	-203	-267	-206
1	CEH RS18	151	161	0.02	2	5	0	10.0	-192	-198	-193	-192	-192	-188	-192	-190	-187	-192	-125	-204
1	CEH RS19	151	161	0.02	2	5	1	10.0	-202	-200	-195	-198	-202	-205	-204	-203	-207	-198	-229	-201
1	CEH RS20	151	161	0.02	2	5	1	10.0	-212	-185	-202	-211	-216	-217	-221	-224	-226	-208	-233	-207
1	CEH RS21	151	161	0.02	2	5	1	10.0	-211	-195	-196	-205	-209	-216	-223	-225	-221	-199	-189	-203
1	CEH RS22	151	161	0.02	2	5	1	10.0	-198	-203	-196	-195	-196	-199	-198	-198	-199	-190	-233	-198
1	CEH RS23	151	161	0.02	2	5	1	10.0	-204	-194	-194	-200	-205	-208	-212	-209	-211	-200	-191	-202
1	CEH RS24	151	161	0.02	2	5	1	10.0	-196	-179	-187	-195	-201	-203	-201	-204	-203	-200	-221	-198
1	CEH RS25	151	161	0.02	2	5	1.2	10.0	-219	-196	-194	-207	-218	-227	-230	-236	-246	-207	-196	-207
1	CEH RS26	151	161	0.02	2	5	1.2	10.0	-211	-201	-203	-210	-215	-219	-221	-217	-203	-210	-184	-209
1	CEH RS27	151	161	0.02	2	5	1.2	10.0	-218	-221	-208	-210	-217	-219	-221	-224	-222	-209	-256	-212
1	CEH RS28	151	161	0.02	2	5	1.2	10.0	-211	-188	-201	-210	-214	-216	-217	-219	-223	-210	-253	-205
1	CEH RS29	151	161	0.02	2	5	0	10.0	-201	-194	-197	-201	-203	-204	-206	-203	-200	-191	-242	-201
1	CEH RS30	151	161	0.02	2	5	1	10.0	-205	-194	-200	-205	-209	-209	-208	-206	-210	-205	-148	-207
1	CEH RS31	151	161	0.02	2	5	1	10.0	-216	-204	-210	-210	-217	-221	-221	-224	-225	-210	-192	-214
1	CEH RS32	151	161	0.02	2	5	1	10.0	-213	-191	-205	-209	-210	-214	-215	-227	-236	-209	-267	-206
1	CEH RS33	151	161	0.02	2	5	1	10.0	-212	-209	-203	-205	-209	-214	-218	-220	-214	-205	-195	-206
1	CEH RS34	151	161	0.02	2	5	1	10.0	-221	-191	-202	-218	-225	-229	-233	-235	-245	-218	-247	-211
1	CEH RS35	151	161	0.02	2	5	0	10.0	-208	-215	-208	-208	-207	-207	-208	-204	-203	-208	-255	-209
1	CEH RS36	151	161	0.02	2	5	0	10.0	-207	-208	-206	-205	-206	-205	-204	-208	-214	-205	-258	-210

Distance from hole, mm	Test ID	Test Settings							Sliding Gravity								Ave. Grav.	Gravity	Para	P-V Fit
		Start	Stop	Step	Time	Height	Psi	Range	Threshold											
		°2θ	°2θ	°2θ	s	mm	Tilts	°	10%	20%	30%	40%	50%	60%	70%	80%				
1	CEH RS37	151	161	0.02	2	5	0	10.0	-208	-199	-202	-208	-208	-210	-215	-215	-210	-205	-276	-204
1	CEH RS38	151	161	0.02	2	5	0	10.0	-202	-198	-203	-202	-202	-200	-204	-204	-205	-201	-258	-205
1	CEH RS39	151	161	0.02	2	5	0	10.0	-202	-191	-192	-199	-205	-207	-205	-209	-212	-199	-239	-203
1	CEH RS40	151	161	0.02	2	5	0	10.0	-201	-199	-196	-201	-201	-199	-204	-207	-204	-199	-167	-204
1	CEH RS41	151	161	0.02	2	5	0	10.0	-208	-183	-192	-202	-208	-212	-214	-221	-231	-209	-253	-204
1	CEH RS42	151	161	0.02	2	5	0	10.0	-216	-181	-200	-209	-216	-221	-224	-232	-239	-209	-250	-209
1	CEH RS43	151	161	0.02	2	5	0	10.0	-207	-216	-207	-205	-207	-208	-205	-204	-201	-202	-186	-208
1	CEH RS44	151	161	0.02	2	5	0	10.0	-218	-202	-208	-215	-216	-221	-225	-229	-228	-185	-274	-216