Nonlinear Optics for the Determination of Early Stage Fatigue

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1 – Introduction and Motivation

The turbine blades used in power generation plants experience extreme mechanical stress. The concern, of course, is that this repeated mechanical stress may weaken the material. If the blade were to break during use, the damage could be catastrophic. Routine inspections are performed to identify the early signs of failure, but not all damage can be seen by visual inspection. The purpose of this work was to investigate the feasibility of nonlinear optical methods, specifically second harmonic generation (SHG), for the characterization of early stage fatigue in the EPRI sample inventory.

Prior work done on 2024 aluminum set the precedent for this project. Individual samples of 2024 were subjected to tensile deformation and analyzed for the change in SHG signal with respect to deformation. Figure 1 shows that SHG signal decreases as mechanical extension increases into the plastic deformation regime. Due to these promising results, we proposed to apply SHG to characterize the degree of load cycling on intact samples. In addition, SHG should be sensitive to damage near a crack on a failed sample.

2 – Method

The light source used for generating a second-harmonic response was a pulsed 532 nm frequency doubled Nd:YAG laser (Minilite II, Continuum). A basic diagram of the SHG setup is shown in Figure 2. The laser operated at a 10 Hz rep rate with a pulse width of 3-5 ns. Laser power at the sample was ~15 mW. The laser was focused to a spot size of approximately 2.5 mm at the sample. The second-harmonic signal, which occurs at 266 nm, is reflected off two dichroic mirrors to separate the signal from the residual pump light and passed through additional filters before being detected by a photomultiplier tube (PMT). Insertion of a glass slide before the PMT allows for detection of the residual background 532 nm light; the glass absorbs the 266 nm SHG light.

A typical SHG test involved illuminating the sample for 540-600 shots of the laser at each spot. Half of these shots are taken without the glass slide in the optical path and include both SHG and background light. The second half are taken with the glass slide inserted to measure only the background light. Each signal trace was separately integrated with a trapezoidal integration to determine the total signal for that laser shot. The integrated values are then averaged for each of the two sets (signal+background and background-only), and the two averaged values are subtracted to produce a single value for the SHG response from that location. Due to the large beam spot size, a single measurement interrogates many grains, each with their own orientation, which may respond differently to the input signal. Thus, the SHG measurement is a spatial average of the material response of a single sample over the ~2.5 mm spot size. The response from each location was further averaged along the length of the sample to provide a single value characteristic of that sample.

We were supplied with 36 steel samples. In order to remove manufacturing grease and reside prior to SHG testing, samples were lightly cleaned with a small amount of methanol and cotton balls, but only down the scan line of the sample. Each sample was probed on the tension side of the sample at 10 mm intervals along the scan line, totaling approximately 25 spots. Samples that contained a crack were also scanned again at smaller intervals, approximately 2 mm apart on each side of the crack, to analyze any signal change close to the crack. We collected data from 5 spots on each side of the crack. The intense laser light did leave a small mark on the sample surface, but following a conversation with EPRI personnel, it was determined that this slight scarring should not compromise other measurements on the samples.

To account for fluctuations in laser performance from day to day, we identified a standard sample that was tested on 3 spots at the start and end of each round of data collection. The signal response was then compared to the first time it was scanned and was used to scale all other responses to a standard response. This process allows for the data taken on different days to still be compared.

3 – Results and Discussion

Figures 3-11 show the average sample response of all 36 samples, with each marker representing the average of all spots scanned on that sample. Figures 3-10 represent samples that did not form cracks, grouped by the number of cycles: Figure 3 is untested samples, Figure 4 is 150,000 cycles, Figure 5 is 300,000 cycles, Figure 6 is 450,000 cycles, Figure 7 is 600,000 cycles, Figure 8 is 700,000 cycles, Figure 9 is 900,000 cycles, and Figure 10 is 2,000,000 cycles. The samples that cracked after a variable number of cycles are shown in Figure 11. It can be seen throughout all of these figures that there is no significant change in signal from sample to sample. Figure 12 shows the difference between samples with varying degree of load cycling. Each marker represents the averaged response from all samples cycled to the same degree, excluding the cracked samples. Overall, we didn't see significant changes in the signal response with varying amounts of cycles. There appears to be significant sample-to-sample variation, possibly greater than any effect due to the load cycling.

Figure 13 shows a more detailed look at the cracked samples. Here, the red line represents the location of the crack. These results show that there is little change even around the crack where the damage has localized. More graphs that show the response at each position on each sample are attached in Appendix A. In these figures, the red line represents the average response across the entire sample.

4 – Conclusion

In general, the results of this work proved to be inconclusive. We were unable to observe significant differences in the SHG signal with number of cycles or even with the presence or absence of a crack. Variability between samples appears to be the most significant issue. Once all the investigations of the EPRI sample inventory have been completed, and some of these samples are cycled to the point of failure, new information and correlations could emerge. Further work could also be done to investigate the effect, if any, of different surface finishing, or to perform measurements on the compression side of the samples, especially on the cracked samples. Time did not permit these investigations.

Figures

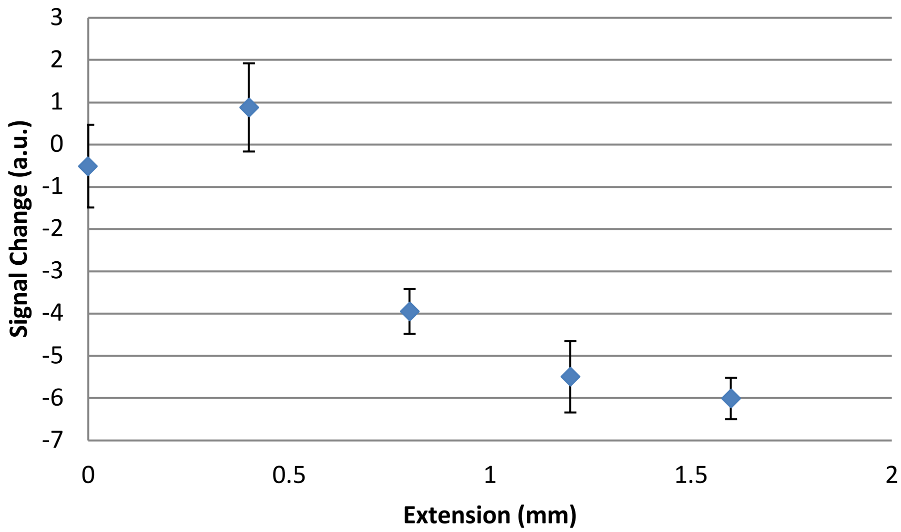

Figure 1. Change in SHG response from professionally polished 2024 aluminum samples due to tensile deformation. Extensions greater than ~0.4 mm have entered the plastic regime.

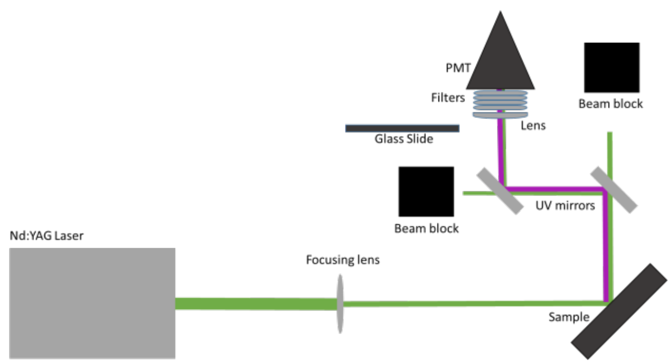

Figure 2. SHG experimental setup. The glass slide is inserted into the beam path for background measurements.

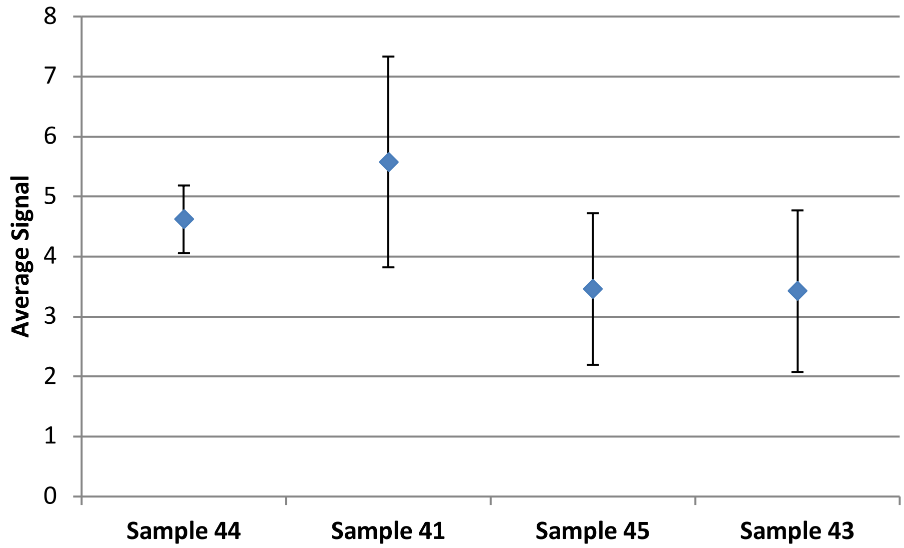

Figure 3. Each marker represents the averaged signal response across the entire sample of four samples that were uncycled.

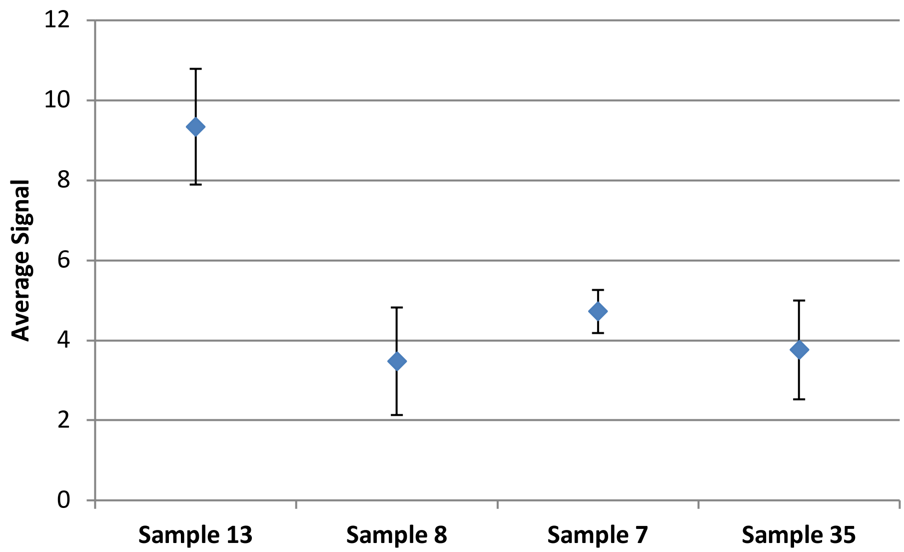

Figure 4. Each marker represents the averaged signal response across the entire sample of four samples that were cycled 150,000 times. (As discussed in the Appendix, Sample 13 proved difficult to work with and did not give very consistent results. It may be an outlier on this graph.)

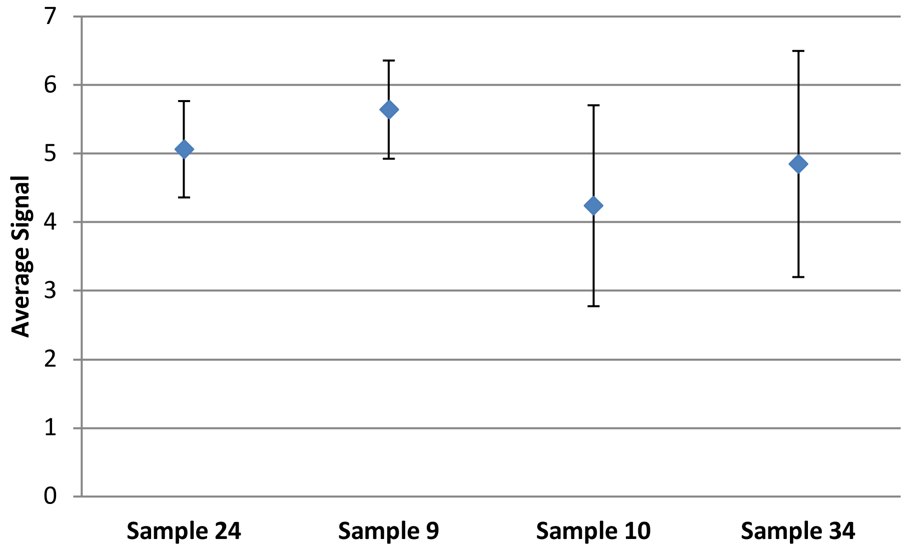

Figure 5. Each marker represents the averaged signal response across the entire sample of four samples that were cycled 300,000 times.

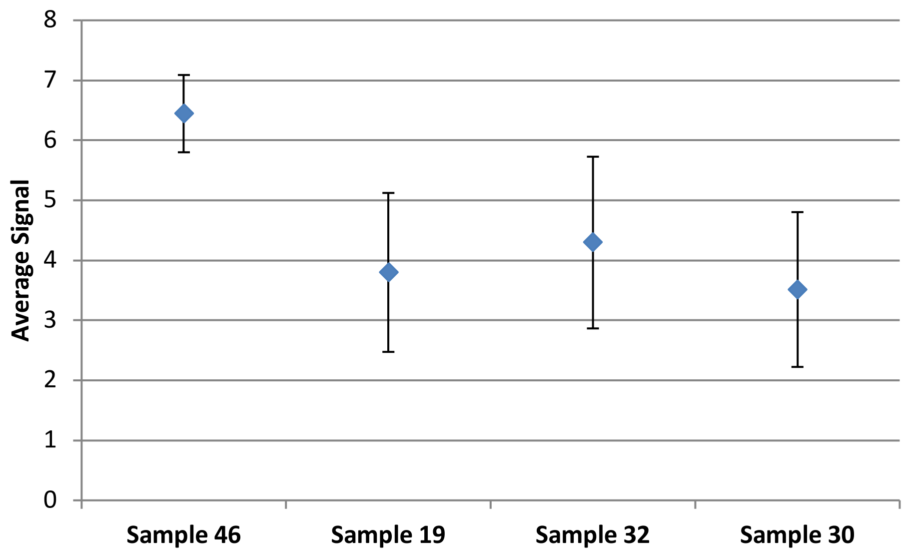

Figure 6. Each marker represents the averaged signal response across the entire sample of four samples that were cycled 450,000 times.

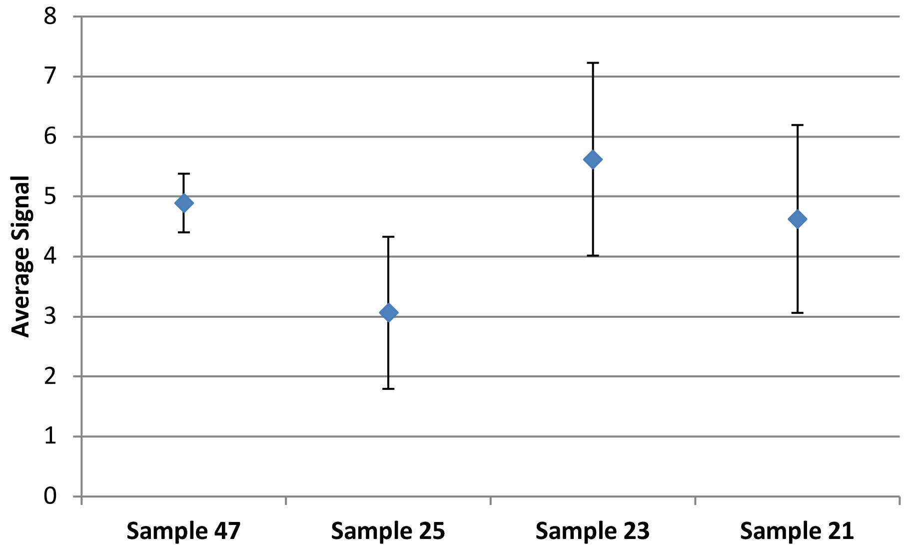

Figure 7. Each marker represents the averaged signal response across the entire sample of four samples that were cycled 600,000 times.

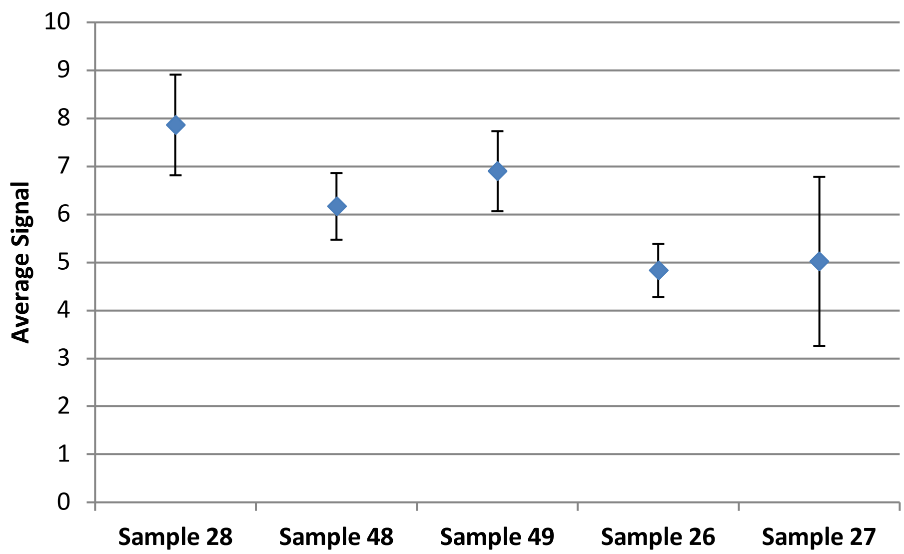

Figure 8. Each marker represents the averaged signal response across the entire sample of four samples that were cycled 750,000 times.

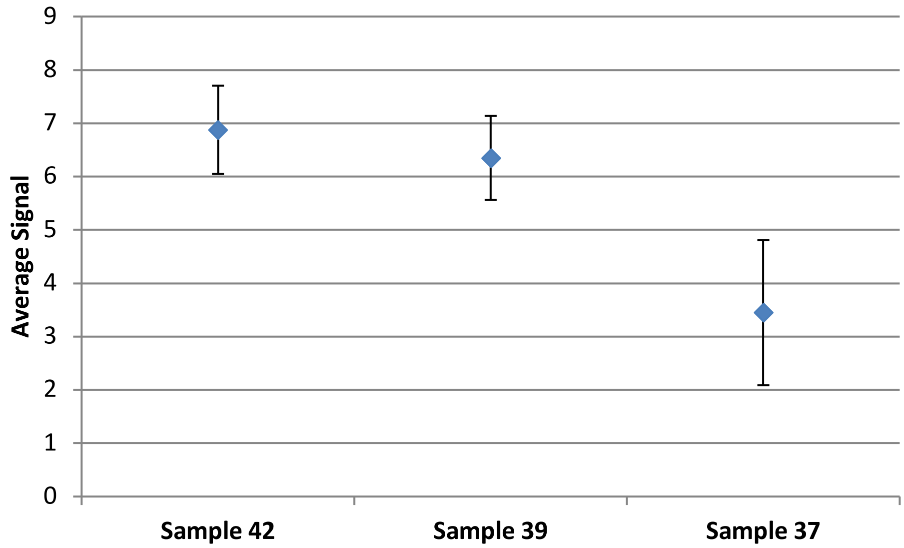

Figure 9. Each marker represents the averaged signal response across the entire sample of four samples that were cycled 900,000 times.

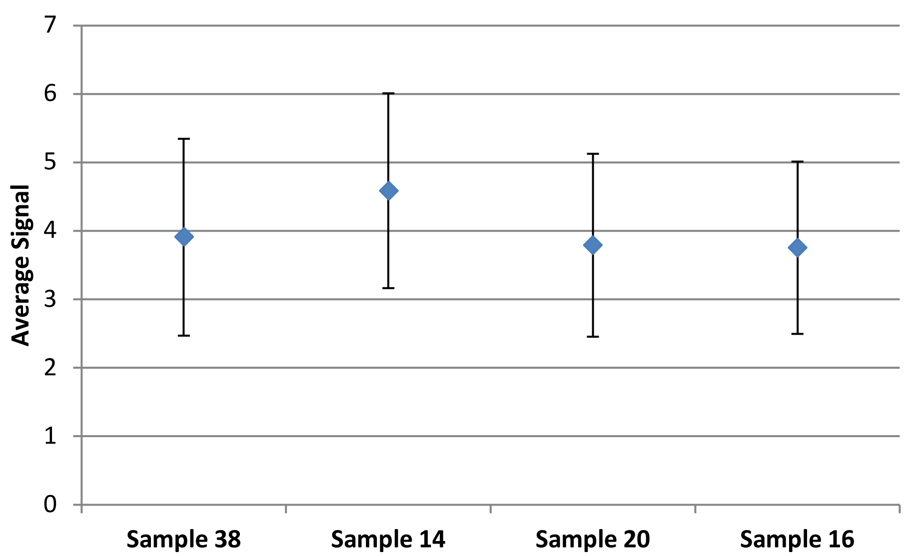

Figure 10. Each marker represents the averaged signal response across the entire sample of four samples that were cycled 2,000,000 times.

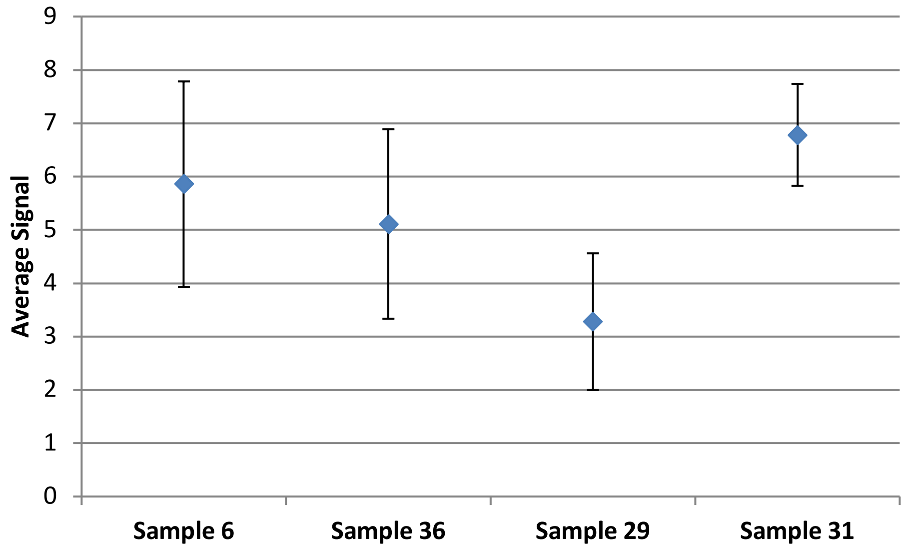

Figure 11. Each marker represents the averaged signal response across the entire sample of four samples that were cycled until they cracked.

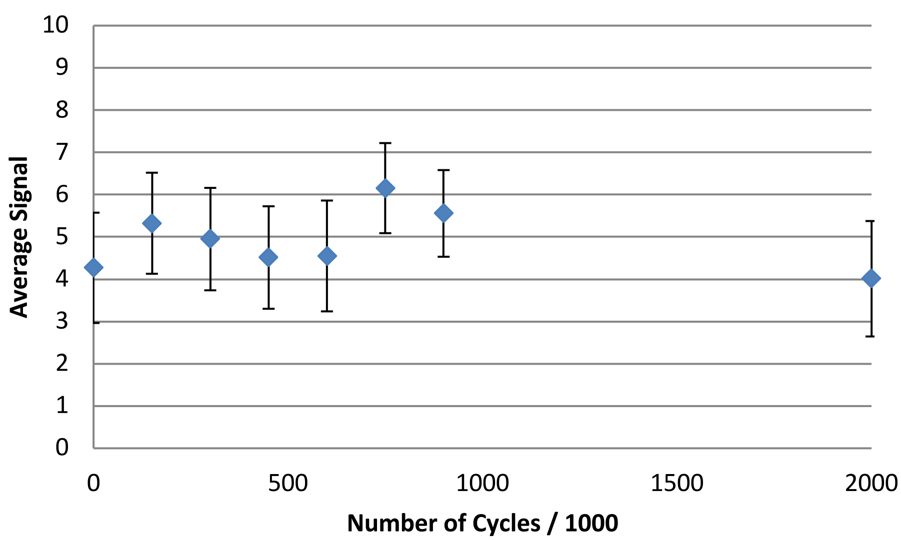

Figure 12. Each marker represents the averaged response of all samples run to the same number of cycles.

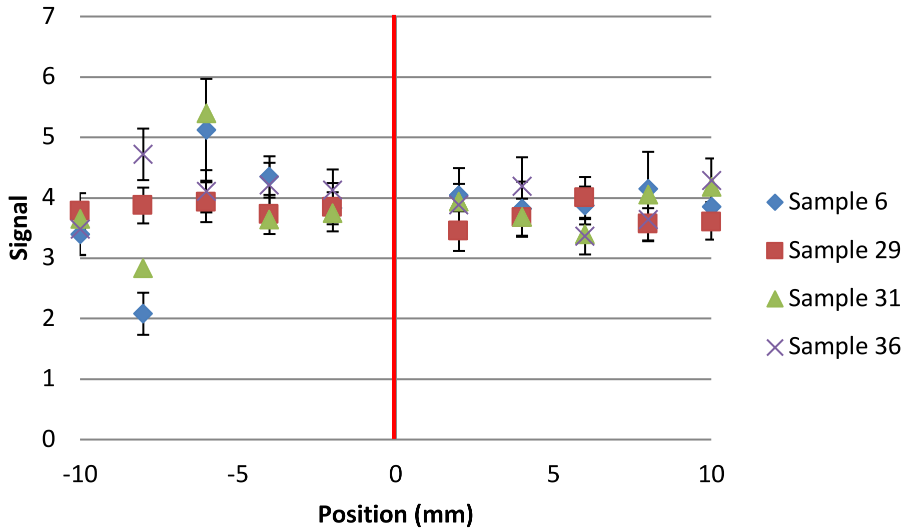

Figure 13. Each set of colored markers represents the 10 spots taken at 2mm intervals on each side of the crack on the sample. The red line in the center represents where the crack was located.

Appendix A

Table A1. This table includes the EPRI data from the samples and the correlated figure number for their SHG data. The red line in each figure indicates the average result across the sample.

Figure #	Specimen ID	Cycles	Stress (ksi)	Note
A1	41C	0	88	
A2	43C	0	88	
A3	44C	0	88	
A4	45C	0	88	
A5	7C	150,000	88	
A6	13C	150,000	88	
A7	8C	150,000	88	
A8	35C	150,000	88	
A9	24C	300,000	88	
A10	34C	300,000	88	
A11	9C	300,000	88	
A12	10C	300,000	88	
A15	19C	450,000	88	
A16	30C	450,000	88	
A17	32C	450,000	88	
A18	46C	450,000	88	
A19	23C	600,000	88	
A20	25C	600,000	88	
A21	21C	600,000	88	
A22	47C	600,000	88	
A23	27C	750,000	88	
A24	26C	750,000	88	
A25	28C	750,000	88	
A26	48C	750,000	88	
A28	37C	900,000	88	
A29	39C	900,000	88	
A30	42C	900,000	88	
A31	49C	900,000	88	
A33	20C	2,000,000	88	
A14	36C	348,957	88	Cracked
A13	6C	318,528	88	Cracked
A32	31C	1,073,548	88	Cracked
A27	29C	784,540	88	Cracked
A34	14C	2,000,000	84	Different stress level
A35	38C	2,000,000	84	Different stress level
A36	16C	2,000,000	80	Different stress level

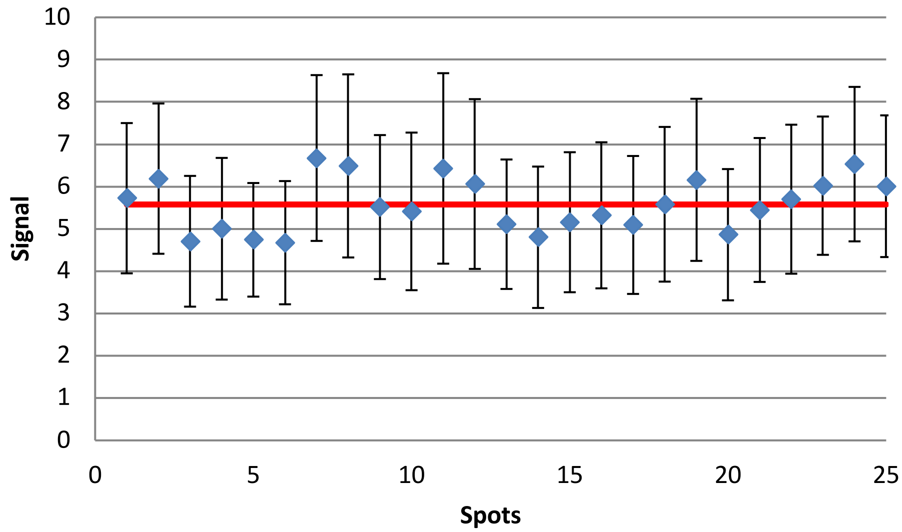

Figure A1. Signal response from spots scanned at intervals of 10 mm across sample 41, untested.

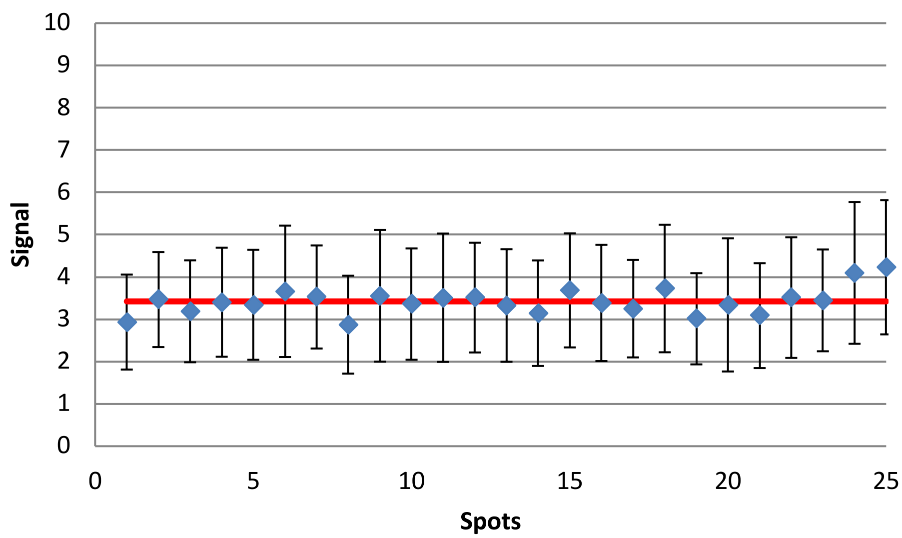

Figure A2. Signal response from spots scanned at intervals of 10 mm across sample 43, untested.

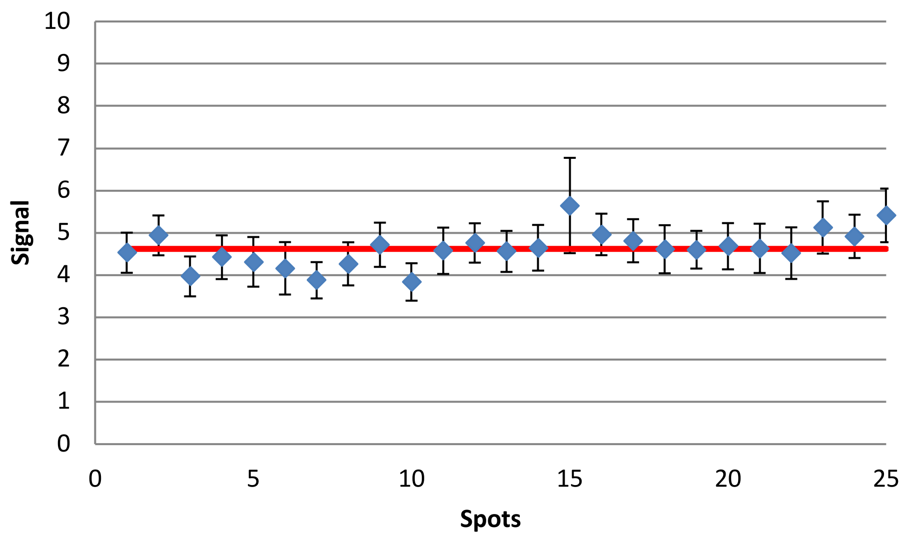

Figure A3. Signal response from spots scanned at intervals of 10 mm across sample 44, untested.

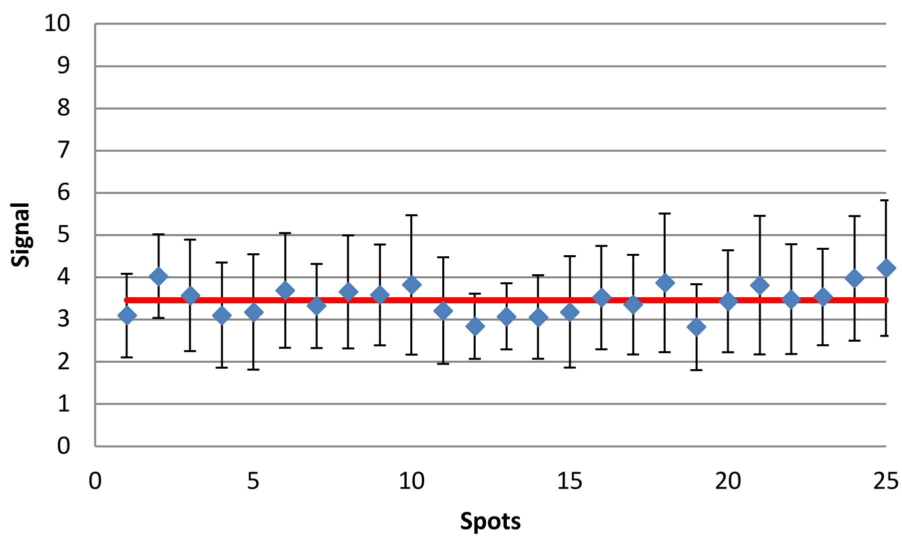

Figure A4. Signal response from spots scanned at intervals of 10 mm across sample 45, untested.

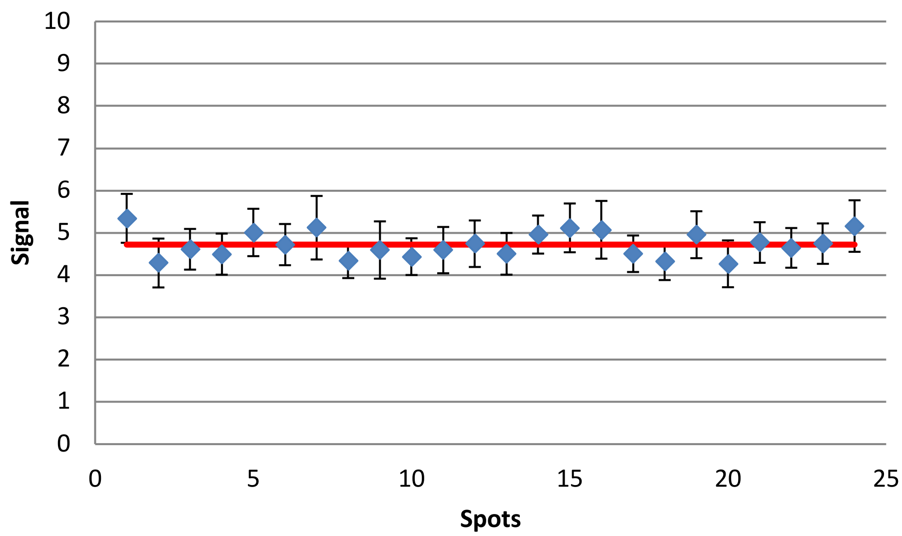

Figure A5. Signal response from spots scanned at intervals of 10 mm across sample 7, loaded to 150,000 cycles.

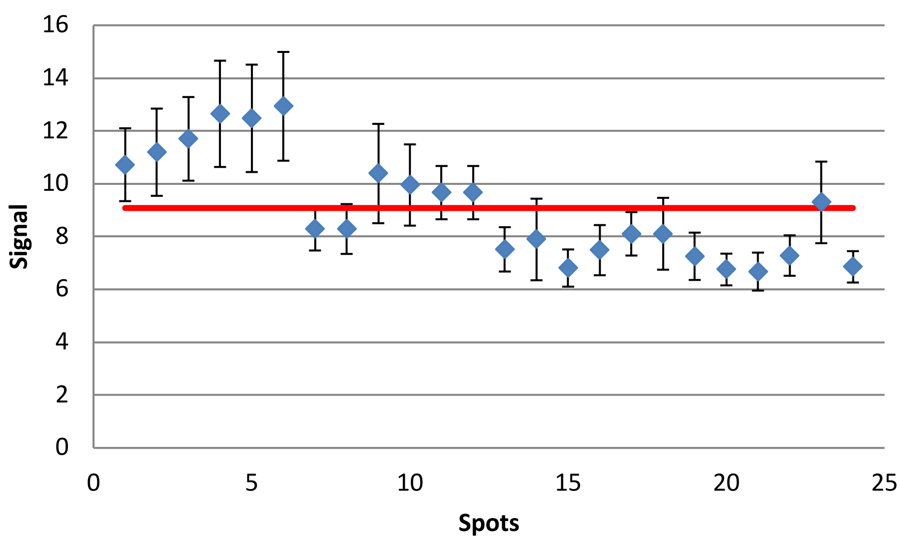

Figure A6. Signal response from spots scanned at intervals of 10 mm across sample 13, loaded to 150,000 cycles. This is just one of three attempts to get consistent signal across sample 13. This sample proved problematic because of laser fluctuations each time this sample was scanned.

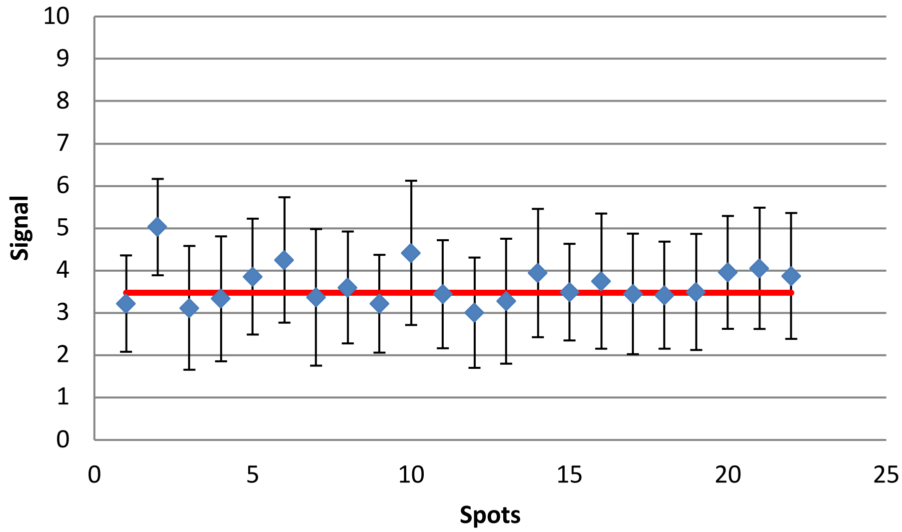

Figure A7. Signal response from spots scanned at intervals of 10 mm across sample 8, loaded to 150,000 cycles.

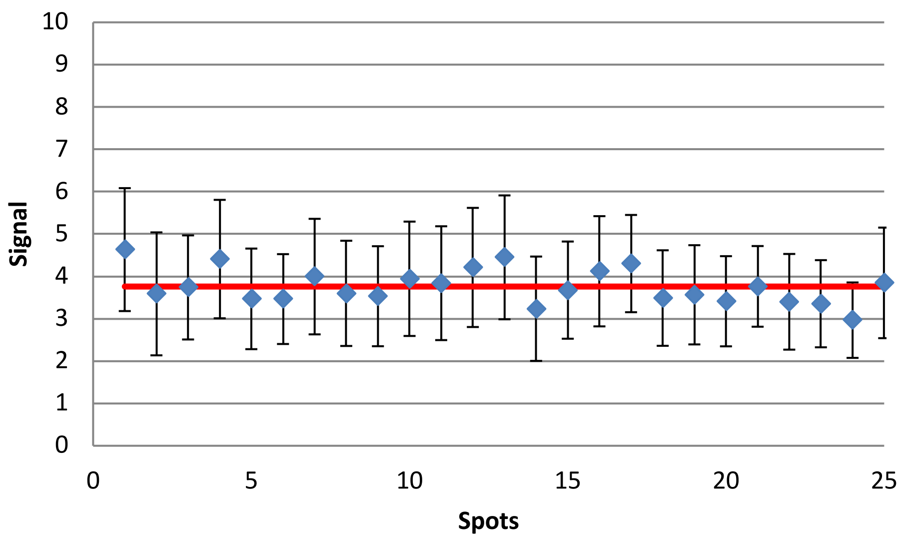

Figure A8. Signal response from spots scanned at intervals of 10 mm across sample 35, loaded to 150,000 cycles.

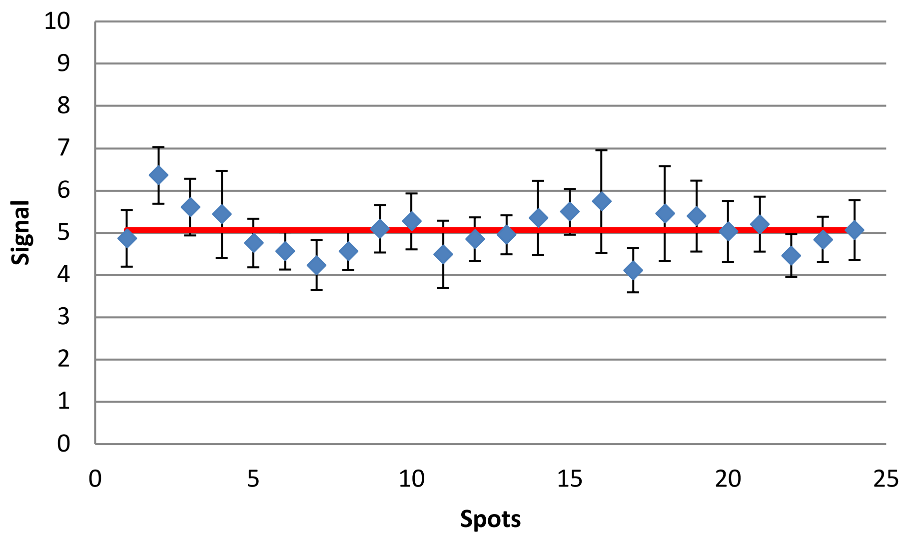

Figure A9. Signal response from spots scanned at intervals of 10 mm across sample 24, loaded to 300,000 cycles.

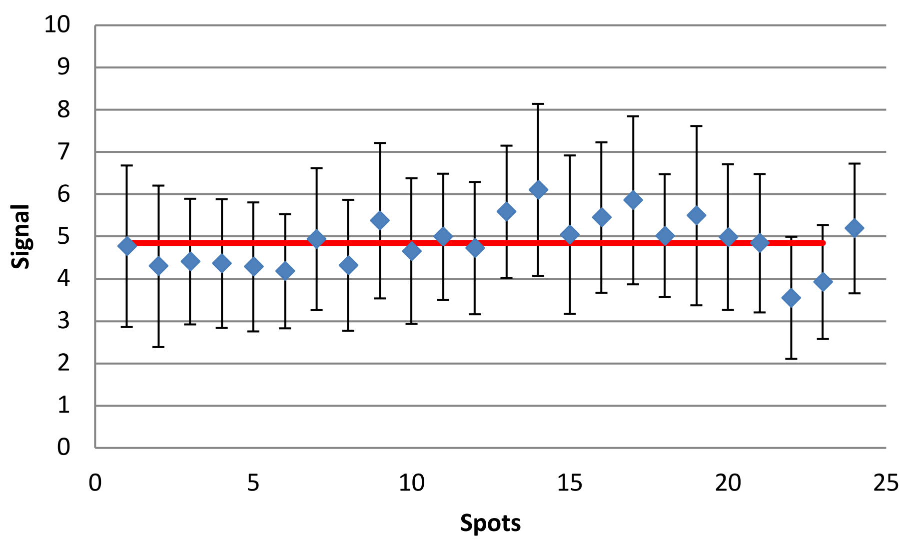

Figure A10. Signal response from spots scanned at intervals of 10 mm across sample 34, loaded to 300,000 cycles.

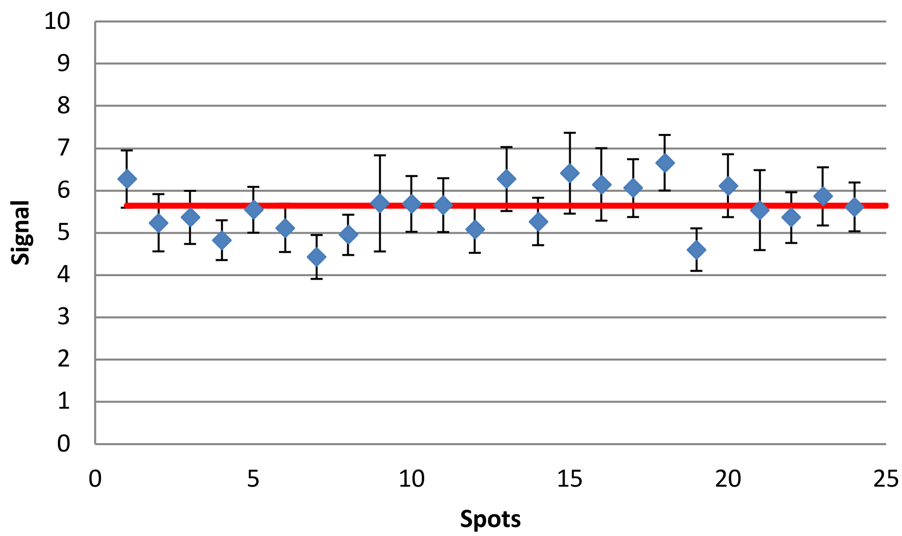

Figure A11. Signal response from spots scanned at intervals of 10 mm across sample 9, loaded to 300,000 cycles.

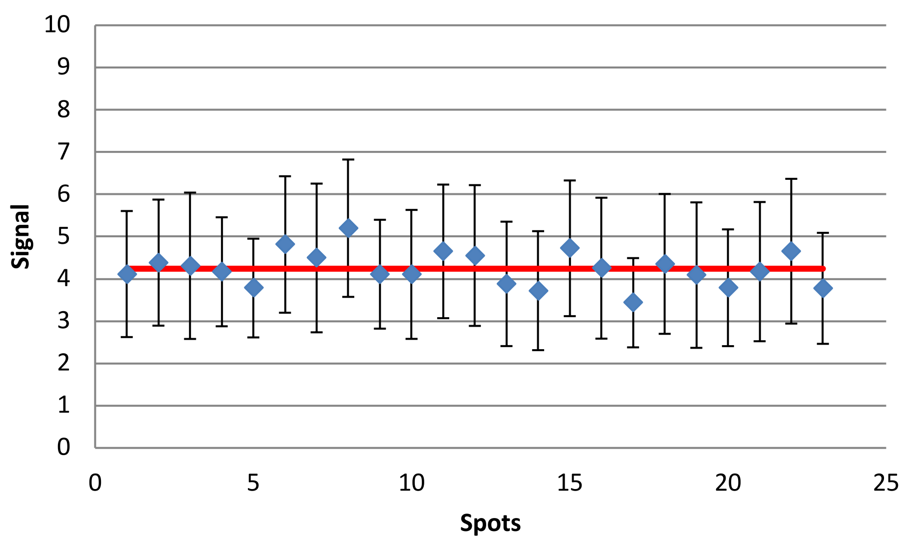

Figure A12. Signal response from spots scanned at intervals of 10 mm across sample 10, loaded to 300,000 cycles.

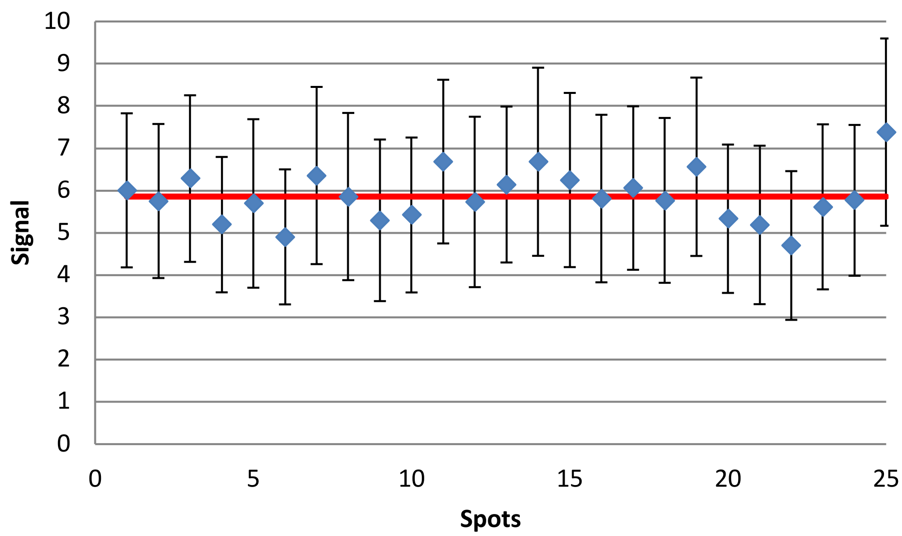

Figure A13. Signal response from spots scanned at intervals of 10 mm across sample 6, loaded to 319,000 cycles and cracked.

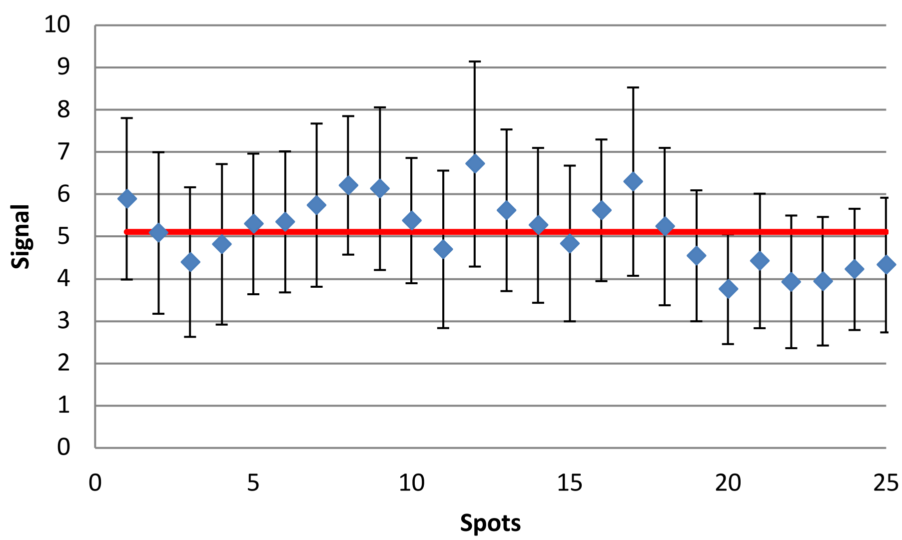

Figure A14. Signal response from spots scanned at intervals of 10 mm across sample 36, loaded to 349,000 cycles and cracked.

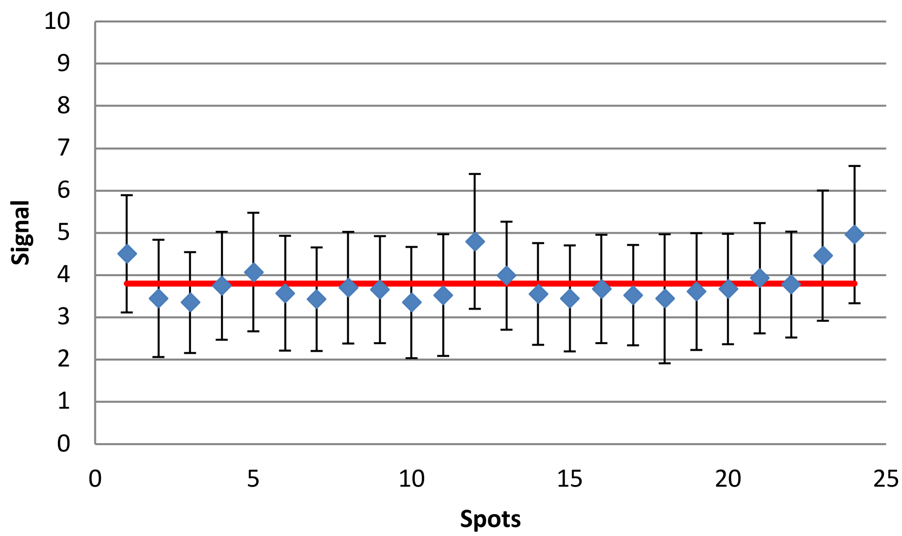

Figure A15. Signal response from spots scanned at intervals of 10 mm across sample 19, loaded to 450,000 cycles.

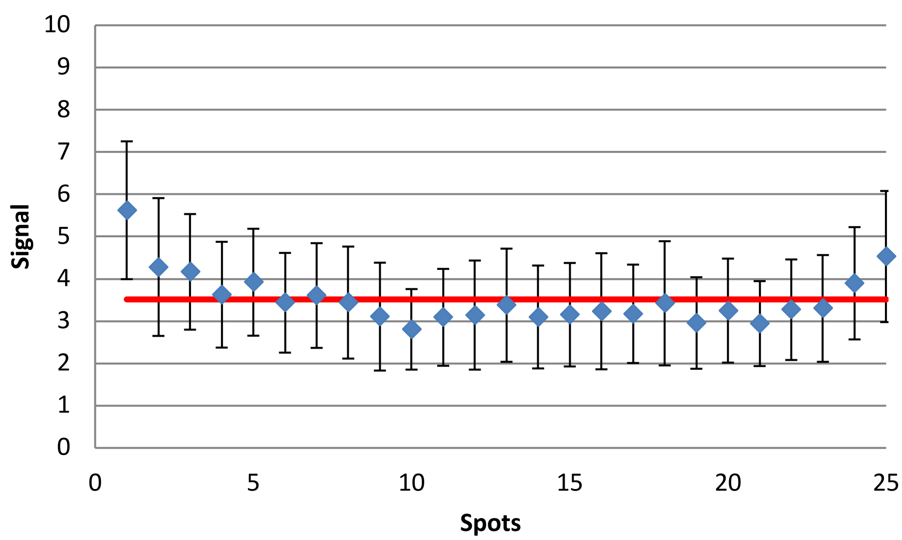

Figure A16. Signal response from spots scanned at intervals of 10 mm across sample 30, loaded to 450,000 cycles.

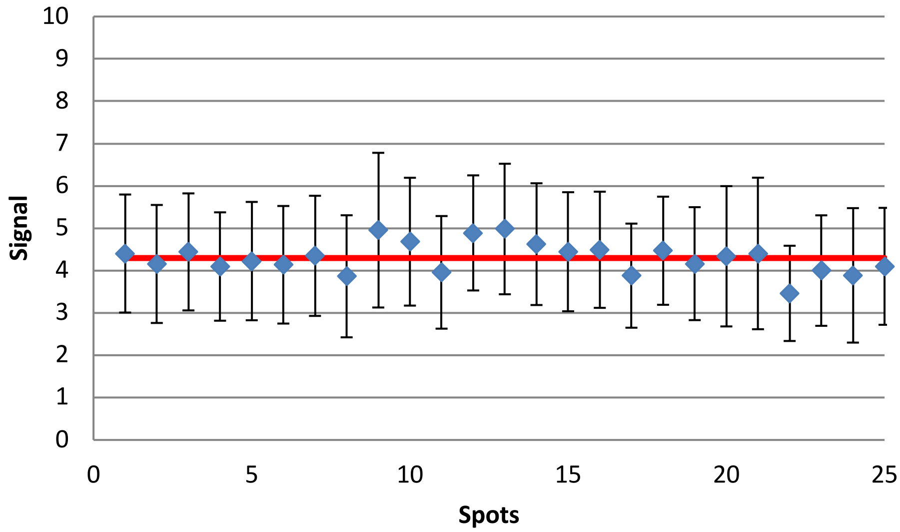

Figure A17. Signal response from spots scanned at intervals of 10 mm across sample 32, loaded to 450,000 cycles.

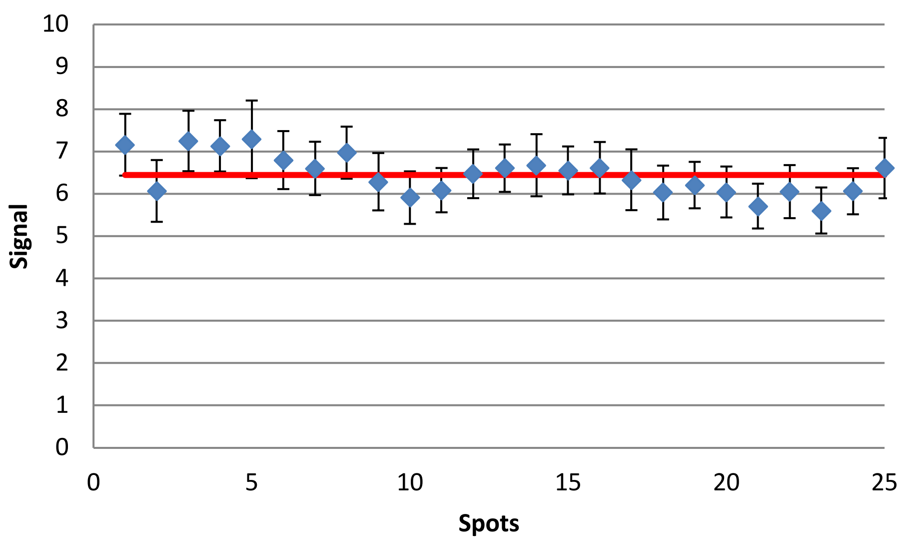

Figure A18. Signal response from spots scanned at intervals of 10 mm across sample 46, loaded to 450,000 cycles.

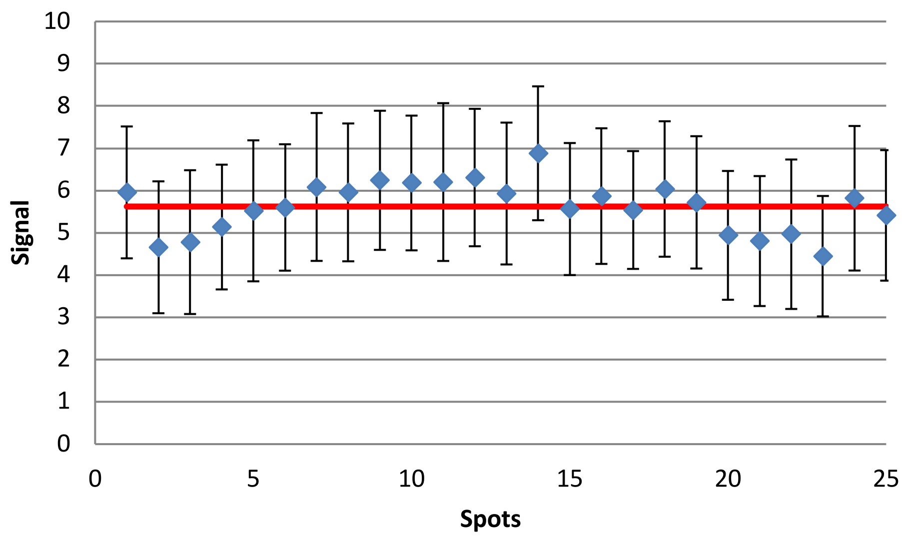

Figure A19. Signal response from spots scanned at intervals of 10 mm across sample 23, loaded to 600,000 cycles.

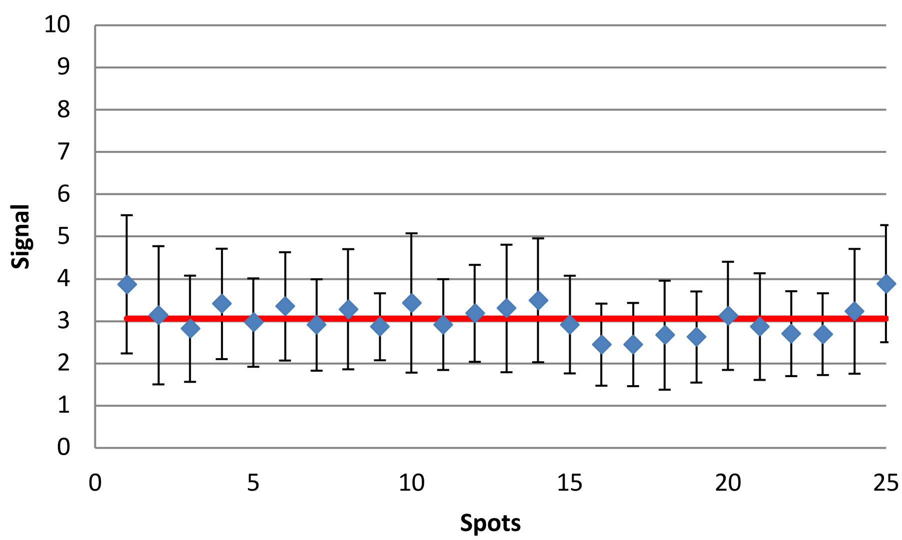

Figure A20. Signal response from spots scanned at intervals of 10 mm across sample 25, loaded to 600,000 cycles.

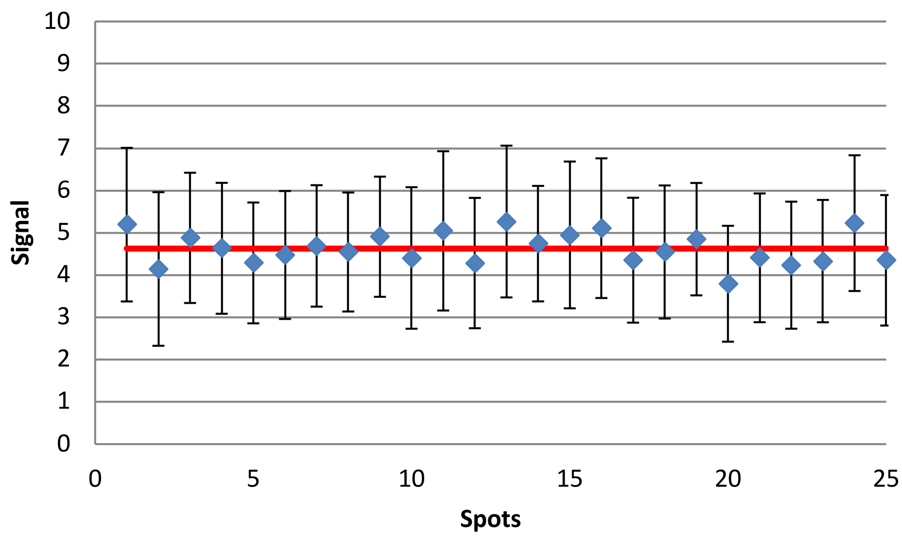

Figure A21. Signal response from spots scanned at intervals of 10 mm across sample 21, loaded to 600,000 cycles.

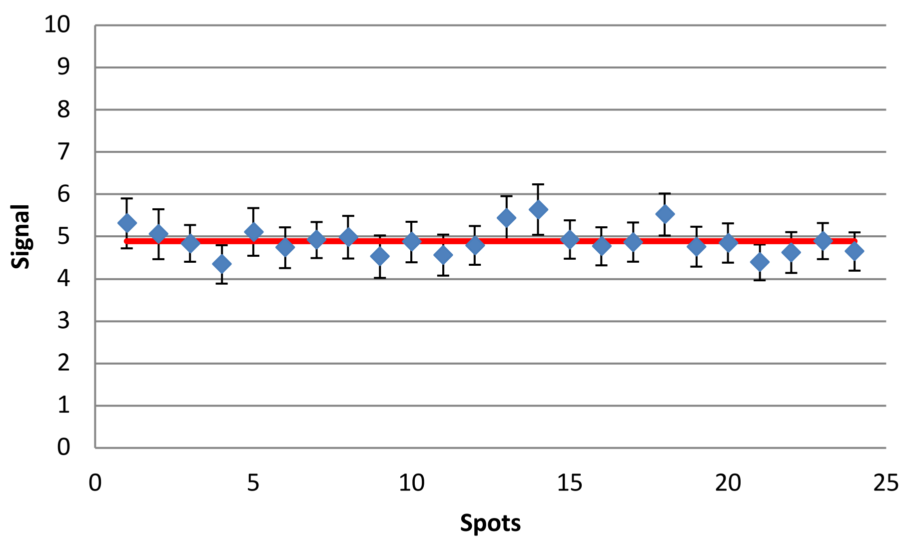

Figure A22. Signal response from spots scanned at intervals of 10 mm across sample 47, loaded to 600,000 cycles.

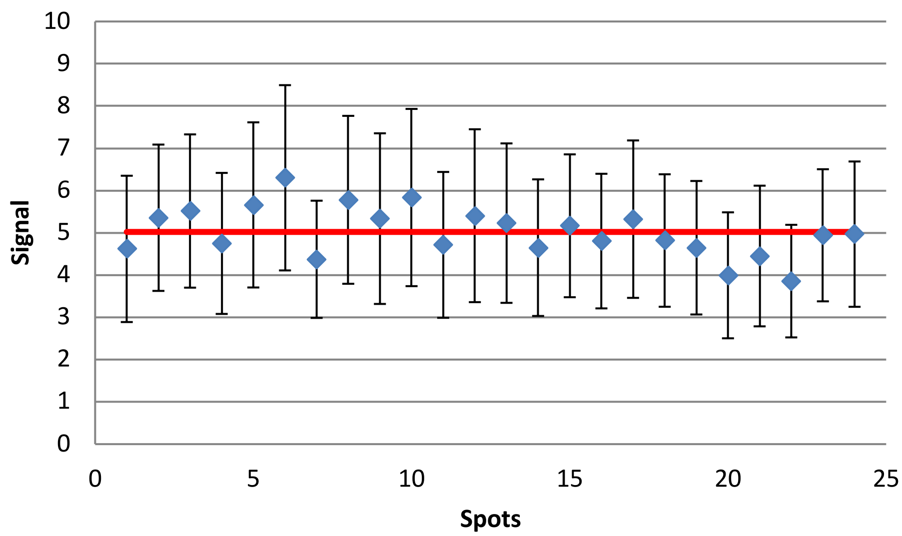

Figure A23. Signal response from spots scanned at intervals of 10 mm across sample 27, loaded to 750,000 cycles.

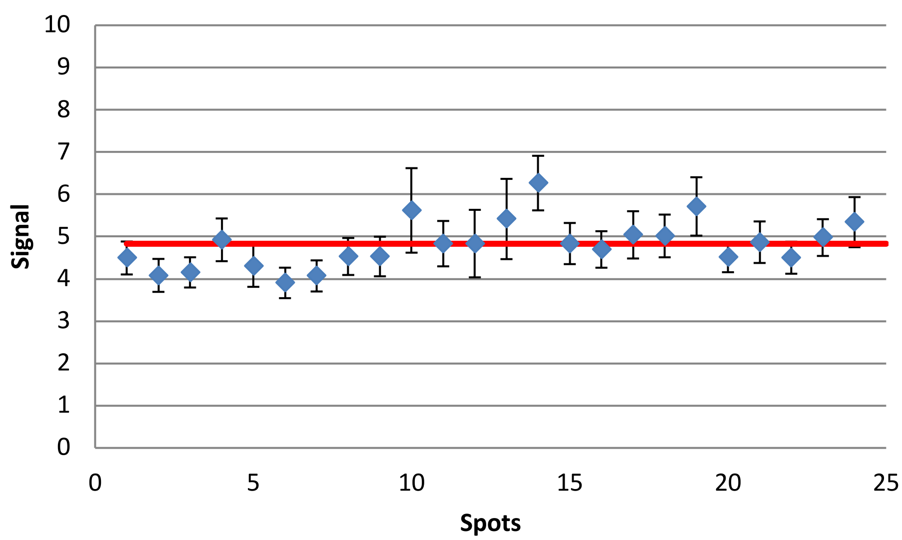

Figure A24. Signal response from spots scanned at intervals of 10 mm across sample 26, loaded to 750,000 cycles.

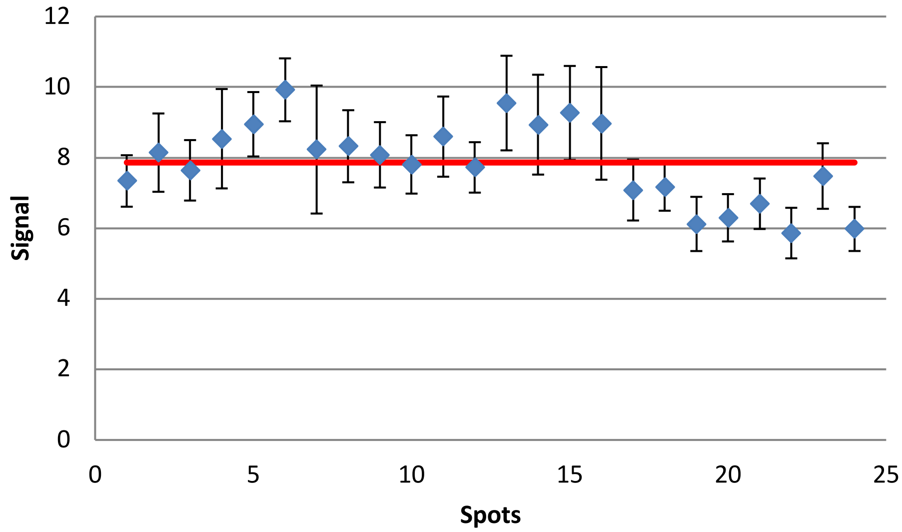

Figure A25. Signal response from spots scanned at intervals of 10 mm across sample 28, loaded to 750,000 cycles.

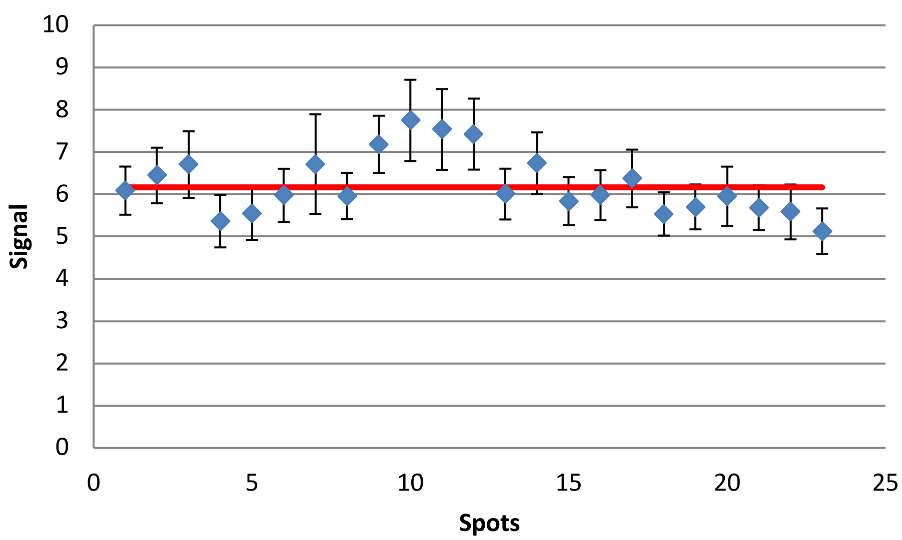

Figure A26. Signal response from spots scanned at intervals of 10 mm across sample 48, loaded to 750,000 cycles.

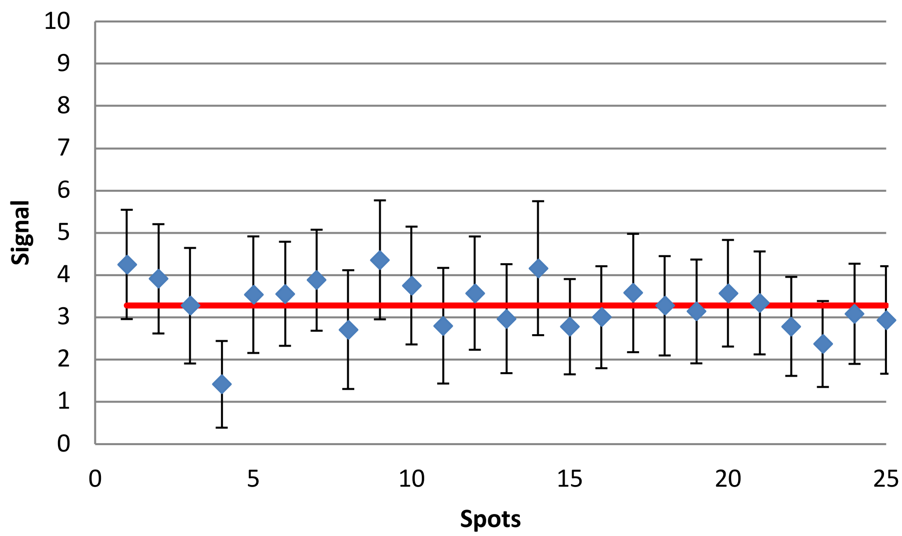

Figure A27. Signal response from spots scanned at intervals of 10 mm across sample 29, loaded to 785,000 cycles and cracked.

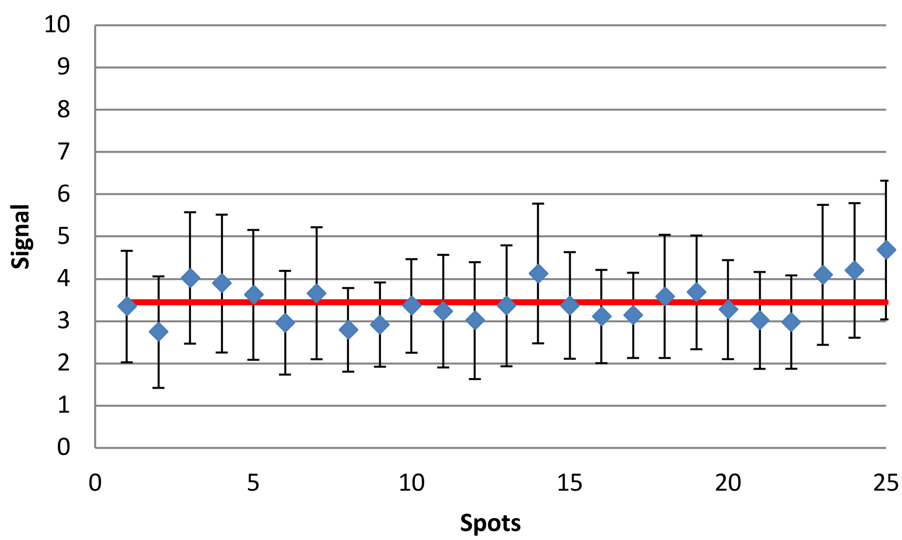

Figure A28. Signal response from spots scanned at intervals of 10 mm across sample 37, loaded to 900,000 cycles.

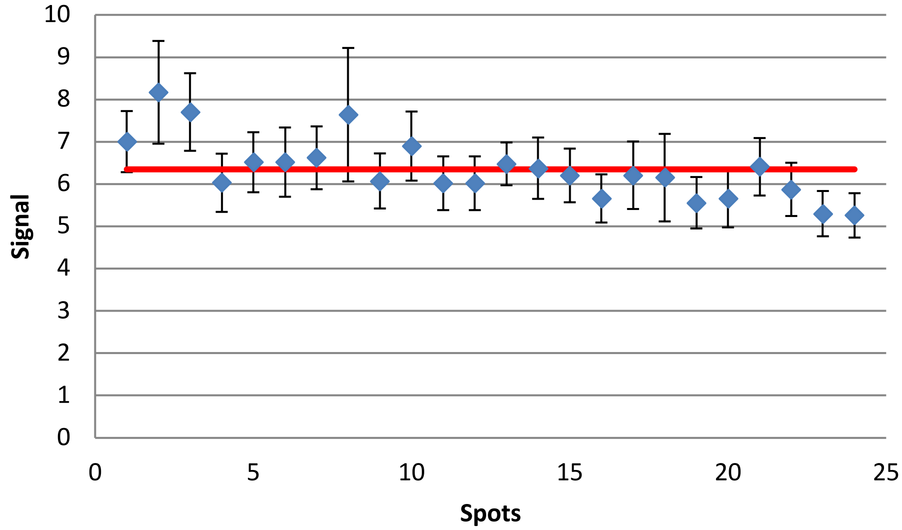

Figure A29. Signal response from spots scanned at intervals of 10 mm across sample 39, loaded to 900,000 cycles.

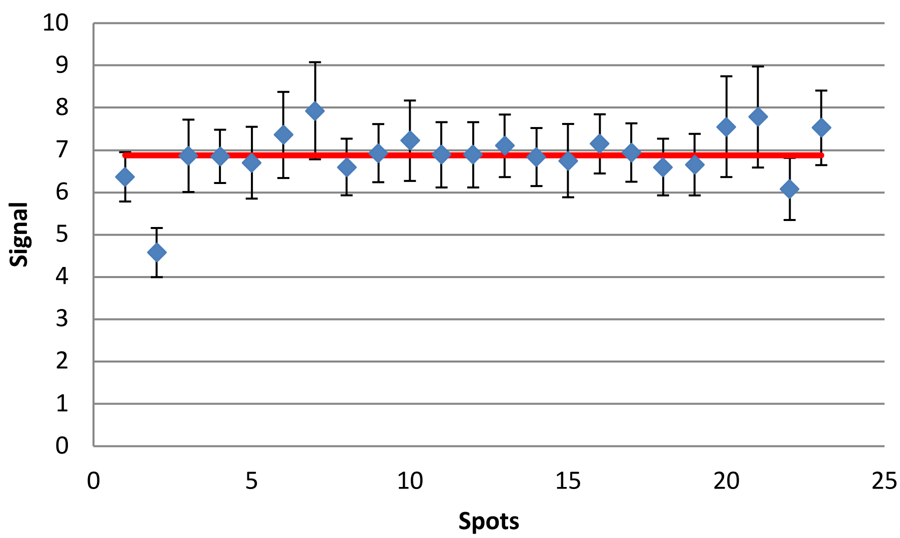

Figure A30. Signal response from spots scanned at intervals of 10 mm across sample 42, loaded to 900,000 cycles.

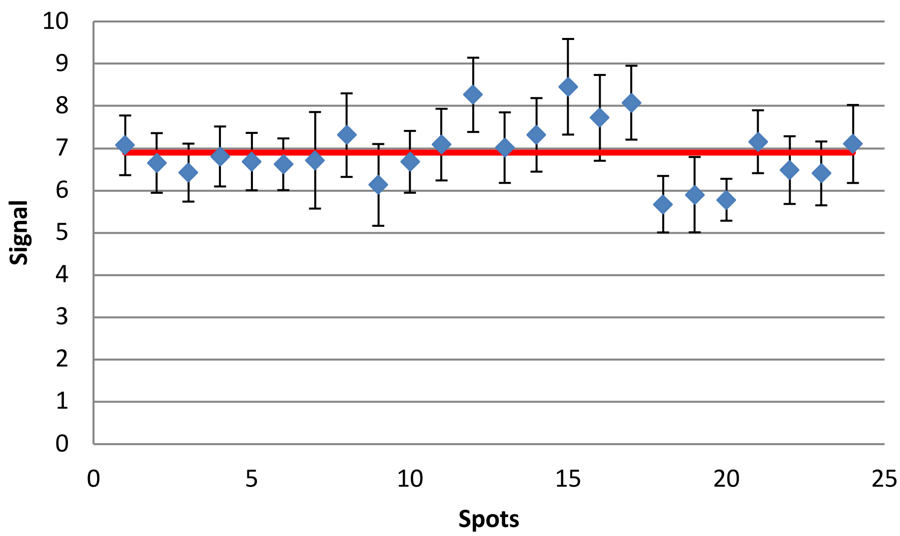

Figure A31. Signal response from spots scanned at intervals of 10 mm across sample 49, loaded to 900,000 cycles.

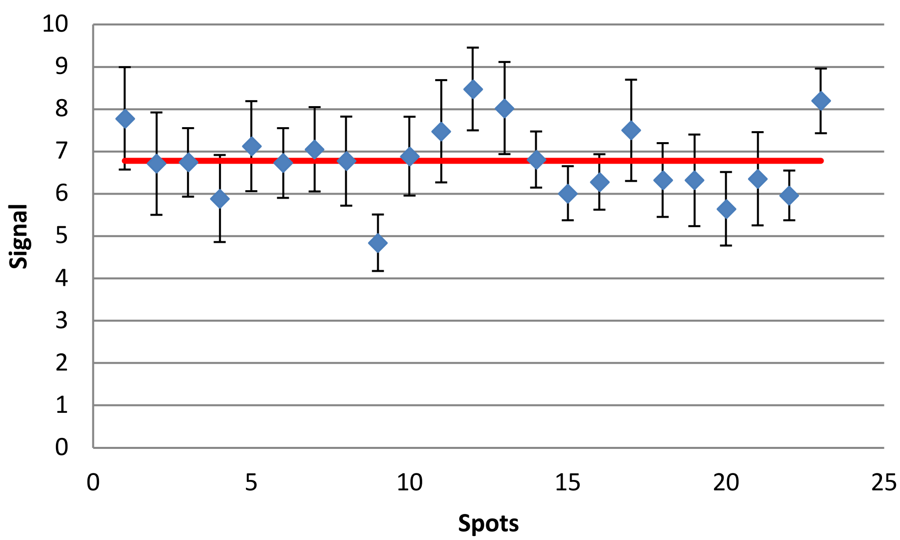

Figure A32. Signal response from spots scanned at intervals of 10 mm across sample 31, loaded to 1,074,000 cycles and cracked.

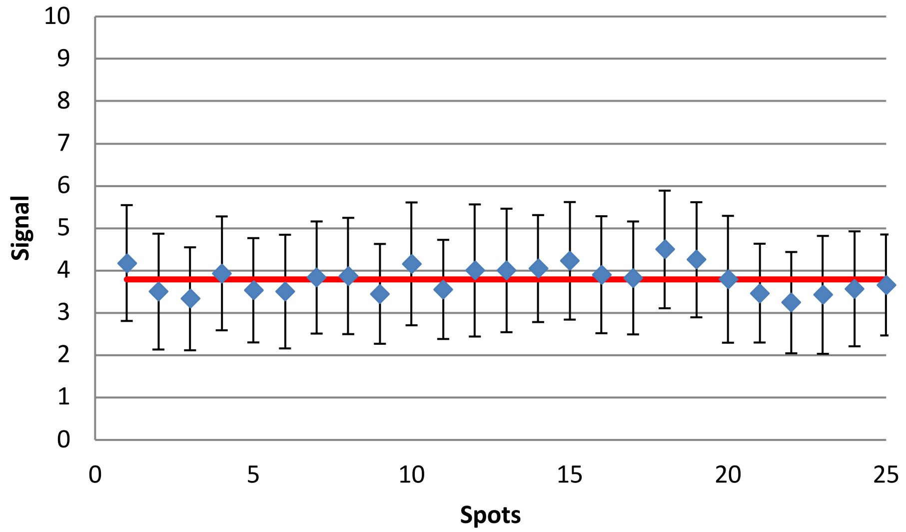

Figure A33. Signal response from spots scanned at intervals of 10 mm across sample 20, loaded to 2,000,000 cycles.

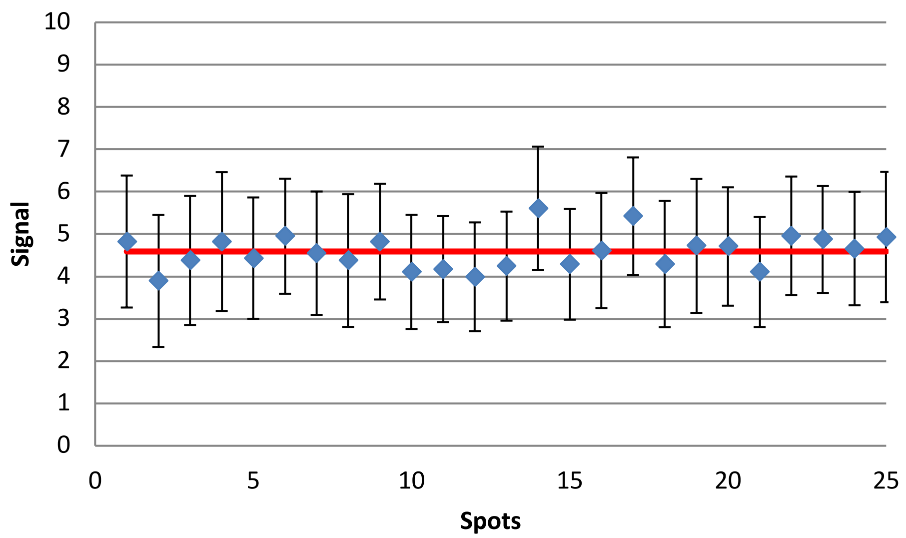

Figure A34. Signal response from spots scanned at intervals of 10 mm across sample 14, loaded to 2,000,000 cycles.

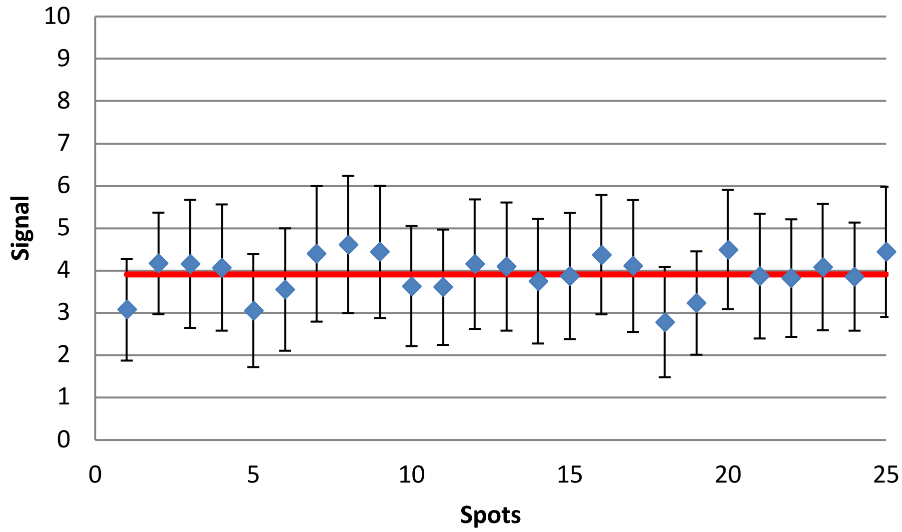

Figure A35. Signal response from spots scanned at intervals of 10 mm across sample 38, loaded to 2,000,000 cycles.

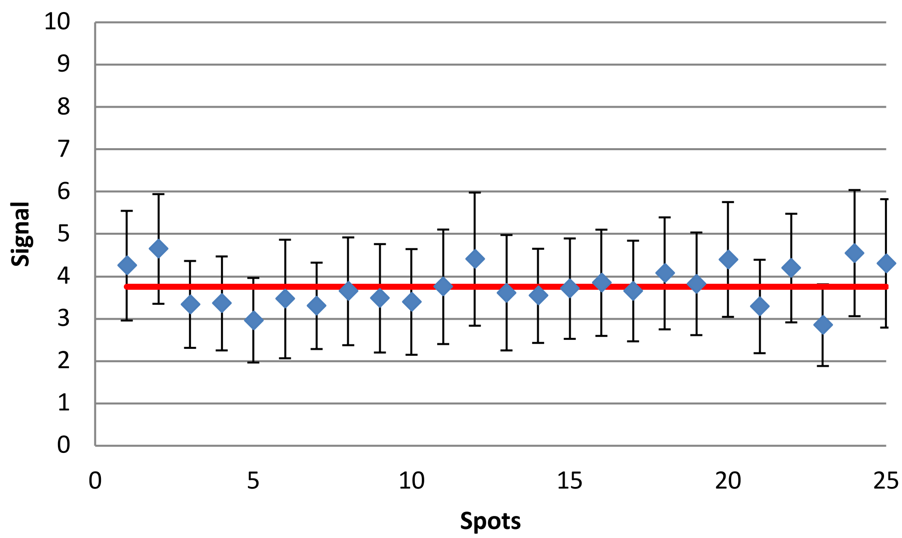

Figure A36. Signal response from spots scanned at intervals of 10 mm across sample 16, loaded to 2,000,000 cycles.