Non-Destructive Residual Stress Measurement Using Eddy Current

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Abstract

A series of experiments to determine whether eddy currents can be used to nondestructively measure the residual stress induced by shot peening in Ti6Al4V and Aluminum 7075 plates was performed. The SmartEddy module, which is a commercially available eddy current testing instrument, was chosen and modified to achieve optimal performance for this research. Experimental results indicate that the eddy current testing system we have developed can measure the intensity of the residual stress induced by shot peening for both Ti6Al4V and Aluminum 7075, and can estimated the stress profile, as a function of depth, for Aluminum 7075.

Introduction

This research, begun in 1990, was undertaken in order to provide a non-destructive technique to measure the near surface residual stress induced in titanium and aluminum alloys by shot peening.

Shot peening has been used in industry for many years. In spite of that, there is still no satisfactory non-destructive technique available to evaluate the residual stress in the near surface. The most commonly used stress measurements are based on X-ray diffraction, a destructive technique. X-ray diffraction is also costly and time consuming. Other methods, such as hole drilling, suffer similar criticism.

Although eddy currents have been used in industry for many years to find cracks and corrosion, very few papers or reports were found claiming to measure the residual stress using eddy currents. In 1995 the NDT (Non-Destructive Testing) group at the Advanced Manufacturing Center of Cleveland State University reported the successful measurement of residual stress in Ti6Al4V. The experiments were done under an ice bath to reduce temperature drift effects, which is one of the major causes of noise when very small eddy current effects are sought. Since that paper appeared , we have succeeded in improving our equipment and technique so that the measurements can be made at room temperature and very quickly.

Experiment

The equipment used in our research is named "SmartEddy". It is a line of personal computer(PC) based eddy current instruments. The latest version, SmartEddy 3.0, uses a personal computer to compile and analyze the eddy current parameters. This is the instrument that was chosen for our research. It was first introduced in 1986, and it was the most advanced commercially available eddy current instrument suitable for this work.

Because of the extremely small magnitude of the conductivity changes induced by shot peening, strict noise control was vital. The thermal drift, as we later confirmed, was the single largest contributor to the drift noise and the total noise as well. In particular, the bridge circuit inside the SmartEddy module is very sensitive to thermal drift. This bridge is a symmetric electric circuit of four elements. Any asymmetry in the four arms of the bridge produces an output signal. We had to modify the as-built SmartEddy module to reduce its sensitivity to noise and drift. The modification was so successful that it greatly reduced the thermal noise. We could then conduct eddy current experiments routinely, at room temperature, and without the ice water bath. Our results are reproducible to ±10 parts per million, and even ± 2 parts per million if the experiments are conducted over a short time interval.

The eddy current testing system which we used includes four major parts: 1) a modified SmartEddy module; 2) eddy current probes (sensors); 3) a sample holding platform; 4) a manual X-Y-Z position vise which permits moving the sample and returning it to precisely the same position. The probe does not move, thereby eliminating noise pulses generated in the cable insulation.

We decided to develop our own software to collect data, because the commercially available software for eddy current testing which came with the SmartEddy module is inefficient for our technique, especially since our technique requires that the data be collected quickly. The signal -to -noise ration can be improved by collecting data more rapidly and by repeating the measurements many times. The code was written to select, at the operator's command, a specific drive level, both amplitude and frequency, and then to automatically sweep through a series of frequencies within the desired frequency range. This frequency sweep is then repeated 100 times. The whole process requires about 3 minute. Output values are read directly off the Analog-to-digital converter inside the SmartEddy module, which contains the averaged Inphase and Quadrature voltages at each frequency. The output data then reflect the sample's conductivity as a function of frequency. This code greatly increases the efficiency of measurement. Now each data point, with appropriate frequency and drive level, requires only 300 micro seconds to obtain, compared with several minutes using the software provided with the machine. The more important advantage is that thermal noise is significantly reduced since each measurement is completed so quickly. Repeating the measurements one hundred times effectively averages out shot time thermal fluctuations and even reduces long term thermal drift.

In order to use this residual stress measurement system, the sample should be of a non-magnetic metal, and the sample's surface should be clean and uniform. Surface defects have a great influence on eddy current response. The sample should have a simple shape. And if the sample is shot peened, the peened surface should be measured and compared to a second, non-peened, surface of the same material.

The samples used in this research were phased from the Metal Store (Cleveland, OH). They are Ti6Al4V -T6 and Aluminum 7075 - T6 plates, as rolled, solution heat treated and artificially aged. The plates were 4 inches square and one-half inch thick.

The chemical composition of the alloys is shown in Tables I and II.

Table I. Chemical Composition of Ti6Al4V Alloy (wt%*)

Alloy	Al	V	Others	Ti
Ti6Al4V-T6	5.25-6.25	3.45-4.20	2.0	Remainder

*values listed are in % by weight of alloy constituent.

Table II. Chemical Composition of Aluminum 7075 Alloy (wt%*)

Alloy	Si	Fe	Cu	Mn	Mg	Cr	Zn	Ti	Other	*Al*
Al 7075	*0.5*	*0.7*	*1.2 - 2.0*	*0.3*	*2.1 - 2.9*	*0.18-0.40*	*5.1 - 6.1*	*0.2*	*0.2*	*Remainder*

* values listed are in % by weight of alloy constituent.

Typical mechanical and physical properties of the alloys are shown in Tables III and IV.

Table III. Typical Mechanical and Physical Properties of Ti6Al4V Alloy[109]

Alloy	Ultimate Strength (psi)	Yield Strength (psi)	Hardness Brinell Number 500kg load 100 mm ball	Electrical Conductivity at 20^0C Fraction of International Annealed Copper Standard
Ti6AL4V-T6	144,000	134,000	325	0.01

Table IV. Typical Mechanical and Physical Properties of Aluminum 7075 Alloy[110]

Alloy	Ultimate Strength (psi)	Yield Strength (psi)	Hardness Brinell Number 500kg load 100 mm ball	Electrical Conductivity at 20^0C Fraction of International Annealed Copper Standard
Aluminum 7075-T6	83,000	73,000	150	0.33

Seven Ti6Al4V plates and Seven Aluminum 7075 plates were sent to the Metal Improvement Company (Twinsburg, Ohio), and various areas were shot peened to the known Almen intensities of 003C, 006C, and 009C and unknown Almen intensities using MI 330 shot. The samples which were shot peened to known Almen intensities were numbered as #1 and #2 for both alloys. The samples with unknown Almen intensities were numbered as “Unknown #1” to “Unknown #10” for both alloys.

The hatched areas of Figure 1 show where the samples were shot peened. A masked area in the center of each sample was left unpeened.

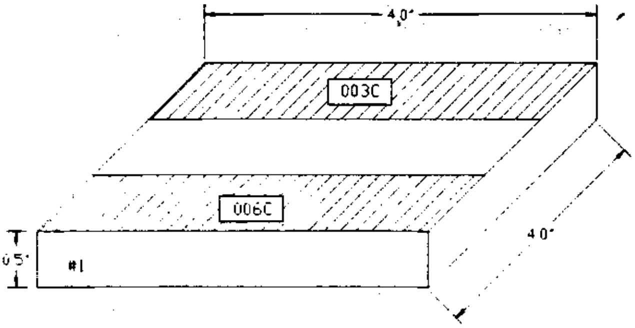

Figure 1. Sample Shot Peened Pattern for Almen 003C and 006C Peening.

As seen in Figure 1, each sample was shot peened with two Almen intensities (known or unknown) in different areas, with an unpeened area in between.

After shot peening, the Ti6Al4V and Aluminum 7075 plates were returned by the Metal Improvement Company, and they were ready for measurement.

The probe was adjusted to be exactly perpendicular to the surface of the sample’s unpeened section, and was held there by its own weight. In order to maximize the eddy current signal, the frequency ranges were chosen to run from 7.031MHz to 7.382 MHz in about 40 kHz steps for Ti6Al4V samples and from 73.24 kHz to 152.54 kHz in about 3 kHz steps for the Aluminum 7075 samples. The drive level was set at 0.8 volt throughout the frequency range to get the maximum possible signal without saturation for all samples. The experimental program was executed and the results were saved to the data file. The Sequence described above was then repeated for the sections of both Ti6Al4V and Aluminum 7075 samples peened to Almen 003C, 006C, 009C and unknown Almen intensities. Finally, all of the sequences were repeated 10 times at different positions in the respective areas.

Results

The results should be plotted on an X-Y graph, with the X axis corresponding to the averaged Inphase output data, and the Y axis corresponding to the averaged Quadrature output data.

The Figures 2 and 3 show the eddy current response pattern for Ti6Al4V and Aluminum 7075 samples peened with known and unknown Almen intensities. These curves serve as reference for comparison with the unknown samples. The unknown samples produced the curves shown in Figures 4 and 5.

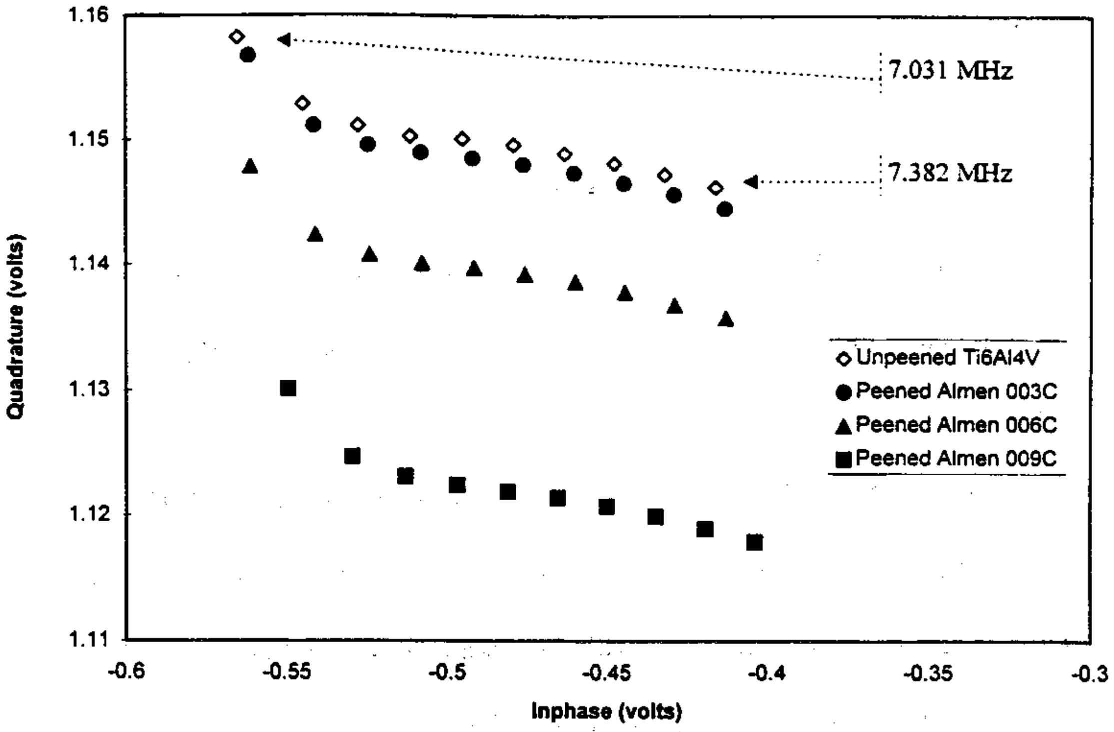

Figure 2. The Average Eddy Current Response for Ti6Al4V Peened to Known Almen Intensities at 10 Different Frequencies

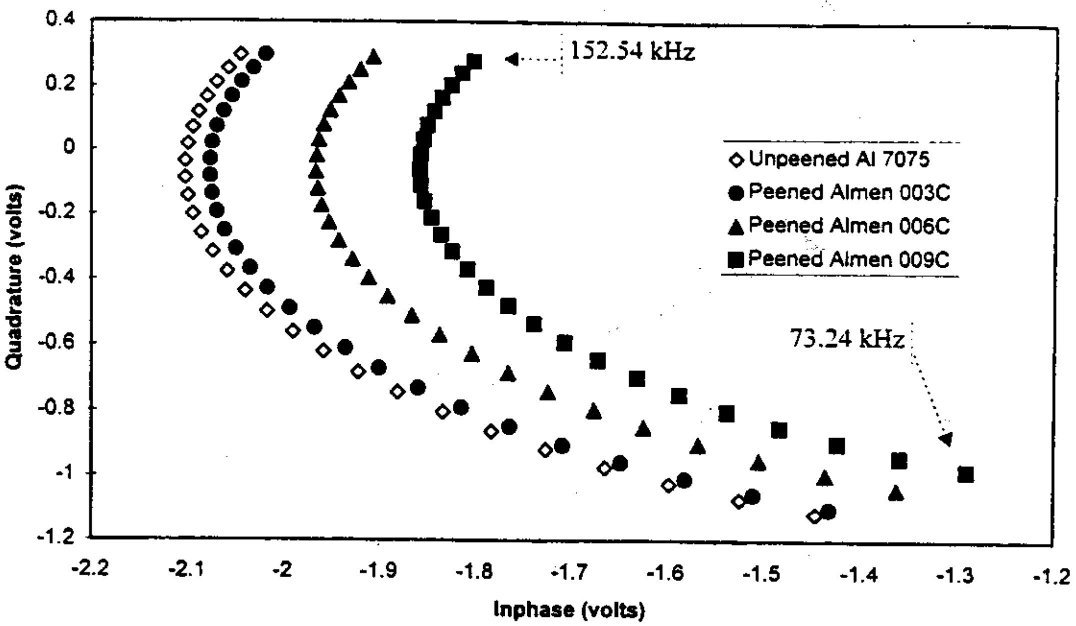

Figure 3. The Average Eddy Current Response for Aluminum 7075 Peened to Known Almen Intensities

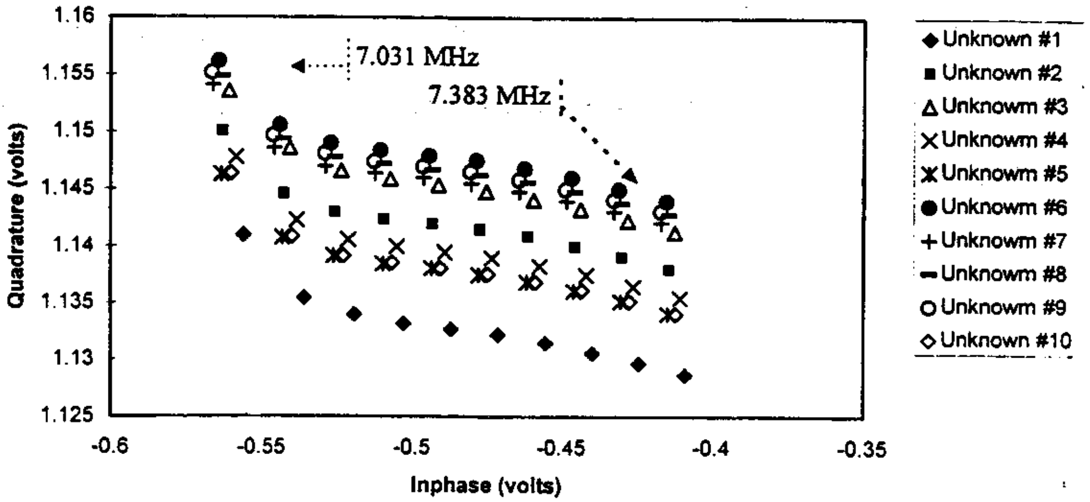

Figure 4. The Average Eddy Current Response for 10 Unknown Almen Intensity Ti6Al4V Samples

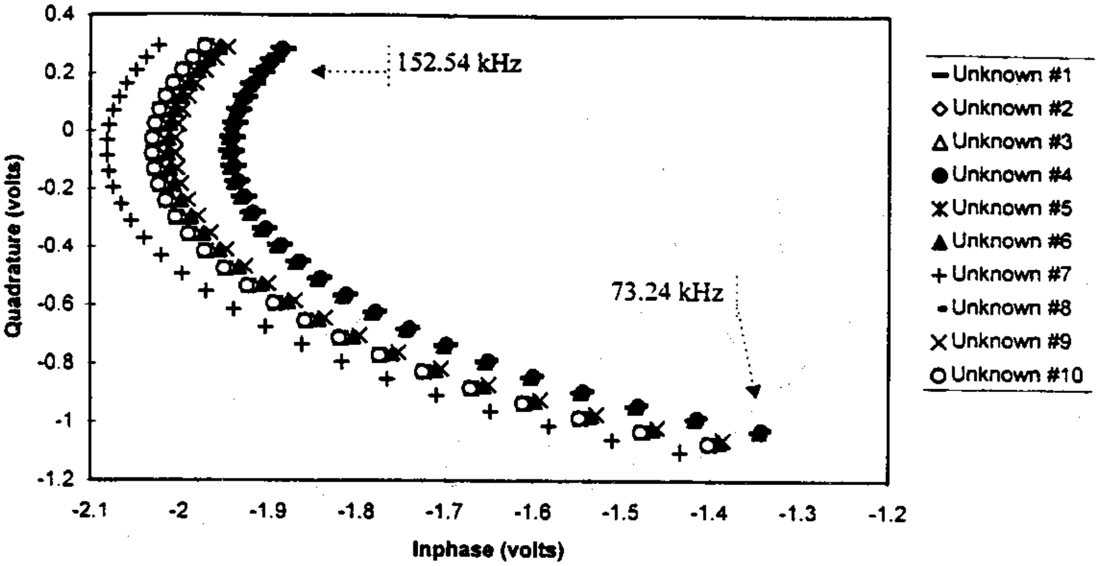

Figure 5. The Average Eddy Current Response for the 10 Unknown Aluminum 7075 Samples

Analysis: Determine shot peening intensity from eddy current data

The critical assumption of the empirical model to determine the shot peening intensity from eddy current data method is that residual stress induced by shot peening increases the resistivity of shot peened metals, at least, aluminum and titanium. Figure 6 supports this assumption.

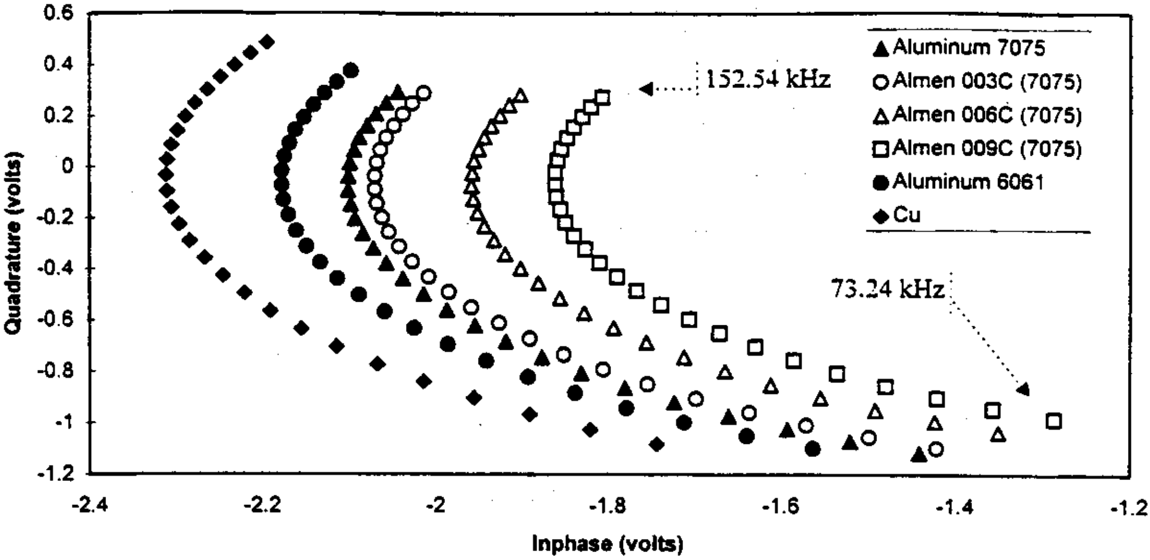

Figure 6. Eddy Current Response for Different Alloys and for Shot Peened Aluminum 7075 (73.24 kHz-152.24 kHz)

The resistivity of copper, aluminum 6061 and aluminum 7075 are 1.7, 4.0 and 5.3 (μΩ.cm) respectively. In Figure 6, with increasing resistivity, the eddy current response curves move towards the positive direction of the X axis. Since the curves for shot peened aluminum also move to the right as the intensity increases, this supports the assumption that peening increases resistivity. The response curve for titanium is far to the right to be shown on this graph.

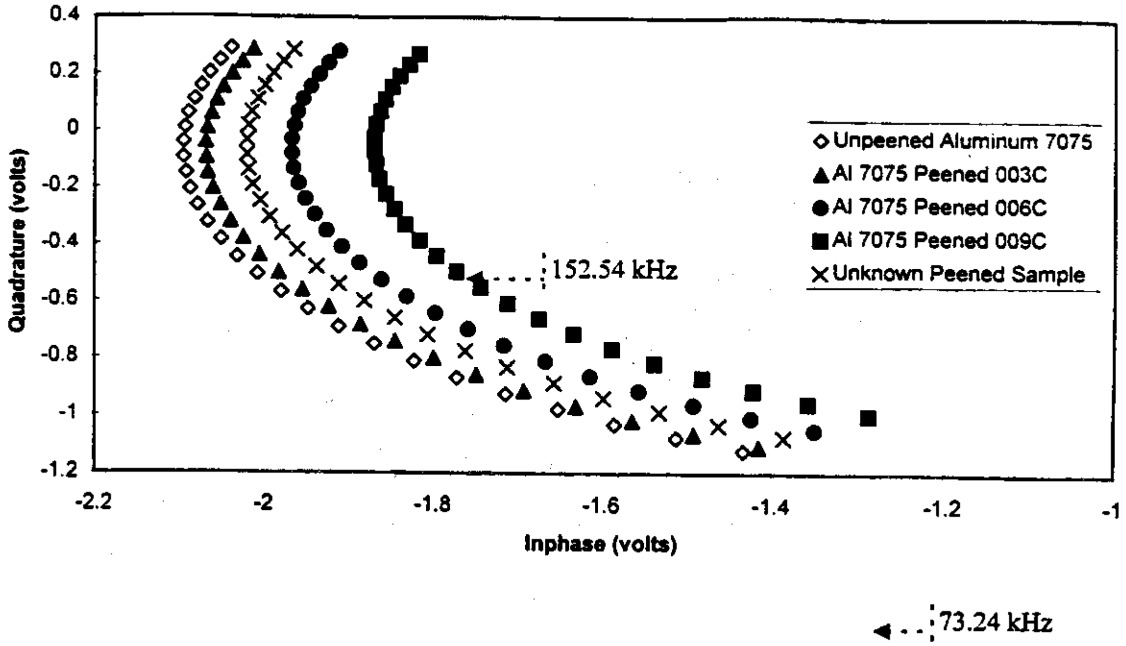

Figure 7. Example Showing How the Peening Intensities of an Unknown Sample Can be Estimated for Aluminum 7075

Figure 7 shows an example of an unknown peened sample displayed among the curves obtained from known samples. The unknown clearly falls between 003C and 006C. It was presumable peened to about 0045C.

Similarly in Figure 8 we see that the unknown titanium sample was peened to 006C.

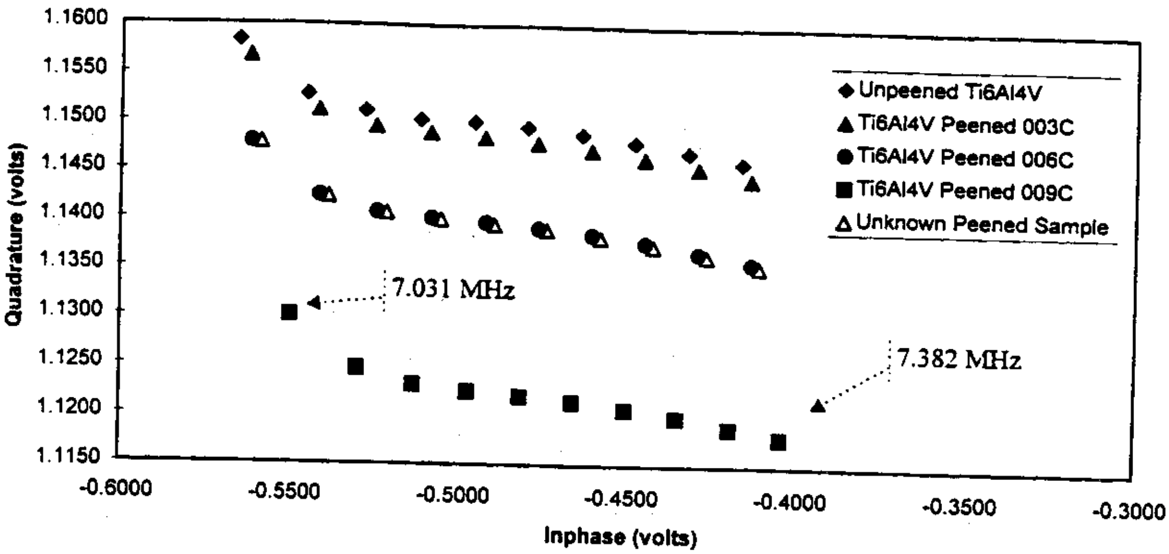

Figure 8. Example Showing How the Peening Intensity of an Unknown Sample Can be Estimated for Ti6Al4V

All of the unknown samples were correctly identified as to their shot peening preparation, within 005C. Metal Improvement Company confirmed our estimates of the peening of the unknowns. The actual results are shown in Tables V and VI

Table V. Comparison of Actual Shot Peening Intensity Levels with the Measured Results for Unknown Aluminum 7075 Samples.

Sample No:	Actual Shot Peening Level (MI Company) Almen Intensity	Measured Results AMC NDT Group Almen Intensity	Difference Between MI and AMC Almen Intensity
Unknown #1	0062 C	0068 C	0006 C
Unknown #2	0042 C	0045 C	0003 C
Unknown #3	0068 C	0066 C	-0002 C
Unknown #4	0068 C	0066 C	-0002 C
Unknown #5	0042 C	0044 C	0002C
Unknown #6	0055 C	005 C	-0005 C
Unknown #7	0028 C	0029 C	0001 C
Unknown #8	0066 C	0065 C	-0001 C
Unknown #9	0055 C	0052 C	-0003 C
Unknown #10	0042 C	0045 C	0003 C

Table VI. Comparison of Actual Shot Peening Intensity Levels with the Measured Results for Unknown Ti6Al4V Samples.

Sample No:	Actual Shot Peening Level (MI Company) Almen Intensity	Measured Results AMC NDT Group Almen Intensity	Difference Between MI and AMC Almen Intensity
Unknown #1	0068 C	0070 C	0002 C
Unknown #2	0068 C	0060 C	-0008 C
Unknown #3	0042 C	0041 C	-0001 C
Unknown #4	0055 C	0060 C	0005 C
Unknown #5	0066 C	0063 C	-0003 C
Unknown #6	0028 C	0031 C	0003 C
Unknown #7	0055 C	0042 C	-0013 C
Unknown #8	0042 C	0040 C	-0002 C
Unknown #9	0037 C	0035 C	-0002 C
Unknown #10	0062 C	0063 C	0001 C

Considering the comparison results from Table V and Table VI, we can see that the determination of the unknown Almen intensities for both Ti6Al4V and Aluminum 7075 samples was very successful: 10 out of 10 Aluminum 7075 samples and 9 out of 10 Ti6Al4V samples were correctly measured with a difference less than 001C.

The accuracy of the experiments is defined as the difference with which the variables can be measured against its true value. The measurements have been shown to be accurate within ± 0.0003 to ± 0.0005 Almen C units as standardized against calibration measurements. The Metal Improvement Company (Mr. Peter Dixon) has stated that MII believes that they shot peen to ± 0.002 Almen C.

Data Analysis - An analytical model to determine the stress-depth curve for aluminum 7075 Samples.

Knowing the Almen intensity of the shot peened material is very important, but it is even more valuable to be able to measure the actual induced residual stress, as a function of depth. The most commonly used method to determine this "Stress-Depth" curve is X-ray diffraction, which is a destructive method. Eddy current data permits us to estimate the "Stress-Depth" curve directly, without destroying the part.

In order to use the eddy current data to predict the "Stress-Depth" curve for Aluminum 7075 samples, we have to assume that the resistivity change of the material is proportional to the stress level.

In order to estimate the stress-depth curve, we first sent the peened Aluminum 7075 samples with known Almen intensities 003C, 006C and 009C to American Stress Technologies, Inc. to do X-ray diffraction from the surface to a depth of 20 mils at 2 mil intervals. Figures 8, 9, and 10 show the results.

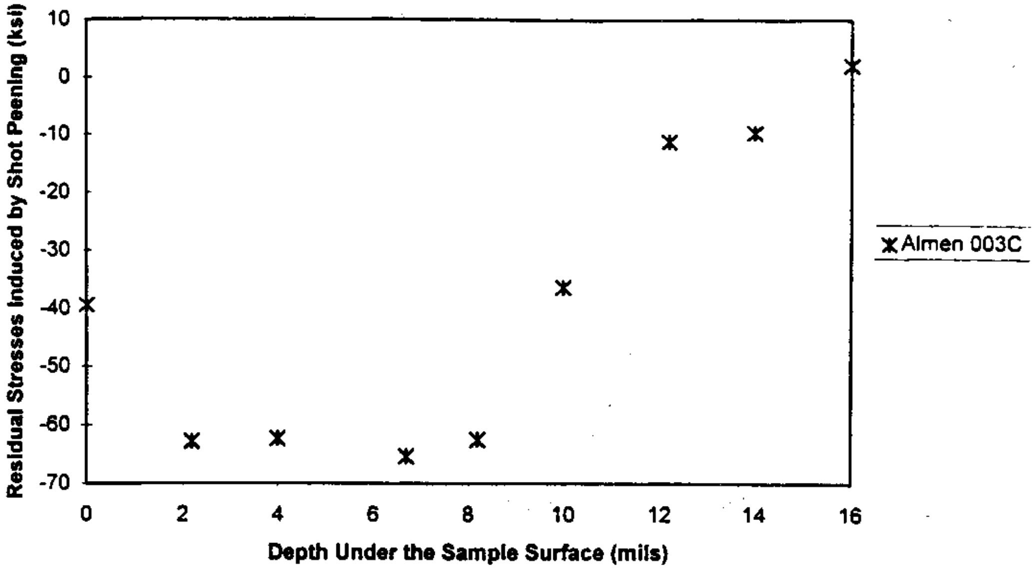

Figure 8. X-ray Diffraction Results for an Aluminum Sample Peened to Almen 003C

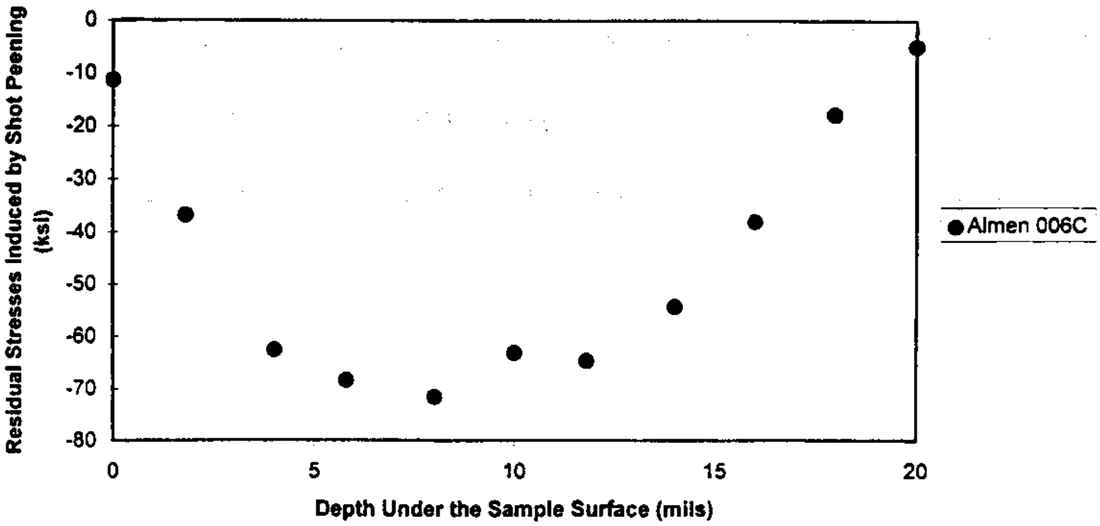

Figure 9. X-ray Diffraction Results for an Aluminum Sample Peened to Almen 006C

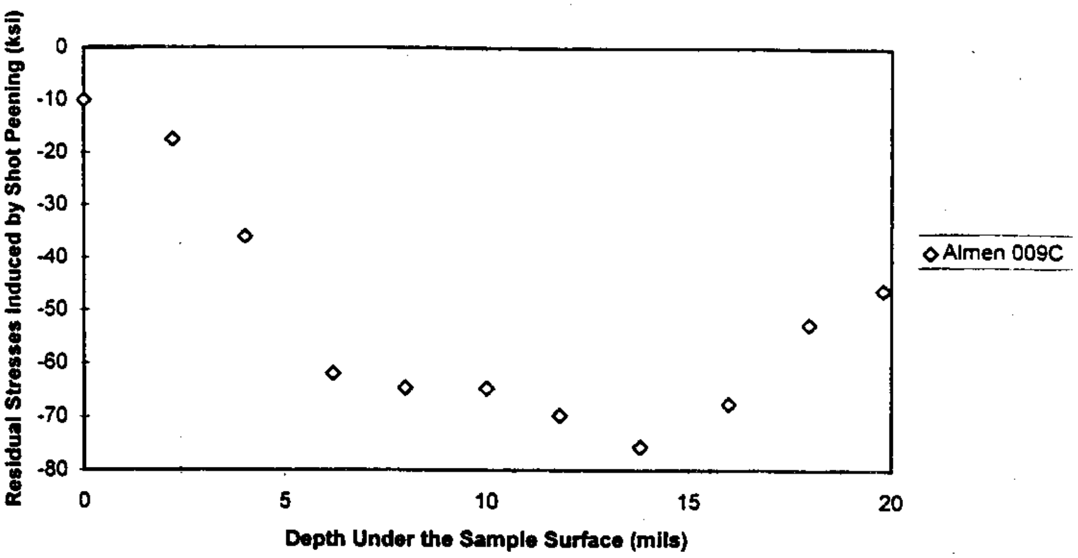

Figure 10. X-ray Diffraction Results for an Aluminum Sample Peened to Almen 009C

In order to get the Stress -- Depth curve, numerical regression was applied to the raw X-ray data with the assumption that the Stress – Depth curve is a third degree polynomial of the form ax^3+bx^2+cx+d. The polynomial curves, based on X-ray diffraction data, for Aluminum 7075 peened to Almen 003C, Almen 006C and 009C are drawn in Figure 11.

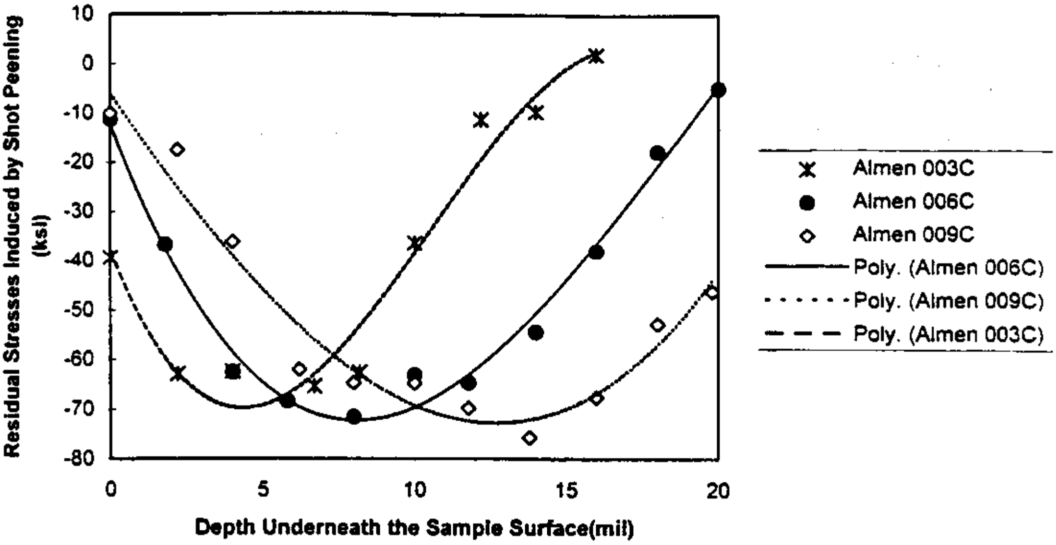

Figure 11. Best Fit to X-ray Diffraction Data Using Polynomial Functions

Figure 11 will be used as the calibration curves for the estimation of the stress-depth curve using eddy current data.

The theory uses the fact that eddy currents are exponentially distributed with depth in the tested sample. Further, the shot peening induced residual stress is also a function of the depth underneath the sample.

Analysis of the electromagnetic fields near the sample surface shows that the eddy current penetration function is

$J_x = J_0 \exp(-x/\delta)$ (where: J_0 is the current density at surface, amperes per square meter; x is the depth from surface, meters; $\delta = \sqrt{\rho / \pi f \mu}$ is the standard depth of penetration of eddy currents, meters. δ is a function of frequency and resistivity in our experiments)

Further, the resistivity change (due to shot peening) under the sample surface is assumed to have the same shape as the stress profile, but inverted. That is, the compressive stress leads to increased resistivity as shown in Figure 12.

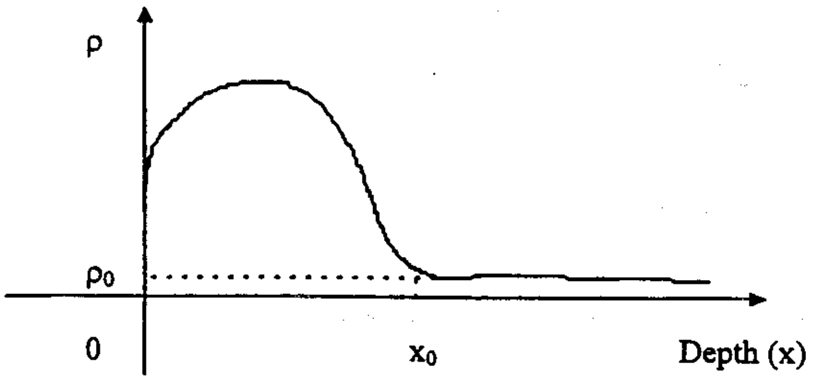

Figure 12. Assumed Resistivity Change (Due to Shot Peening) Under the Sample Surface for Peened Material (ρ: resistivity, x: depth underneath the sample surface, x_0: shot peening depth)

As seen in Figure 12, x_0 is the shot peening depth, and we chose the resistivity change curve for the peened region under the sample surface to be a third degree polynomial function of depth. Therefore, we set

$$\rho(x) = ax^3 + bx^2 + cx + d \qquad (x \le x_0) \qquad \text{Equation 1}$$

$$\rho(x) = \rho_0 \qquad (x > x_0) \qquad \text{Equation 2}$$

Where: $\rho(x)$= resistivity under the sample surface.

x = depth from surface, mils.

ρ_0 = unpeened material resistivity.

x_0 = shot peening depth (at which the compressive stress disappears, and the resistivity becomes ρ_0.

a, b, c and d are the coefficients of the function, to be determined by fitting to the data.

Finally, the total eddy current response signal is considered to be the convolution of the eddy current penetration profile and the resistivity profile under the sample surface. Thus, the difference of the eddy current response between peened and unpeened region can be described as

$$\Delta \mathrm{R(f)} = \int_0^{x_0} (J_0 e^{-x/\delta}) \bullet (ax^3 + bx^2 + cx + d - \rho_0) \bullet dx \qquad \text{Equation 3}$$

where $\delta = \sqrt{\rho / \pi f \mu}$

and Δ R(f) is the difference between peened and unpeened material. Since Δ R(f) depends on frequency, we can use the experimental results for estimating Δ R(f).

We again applied numerical regression to the eddy current response data just as we did for the X-ray diffraction data. Figure 13 shows an example of the regression results:

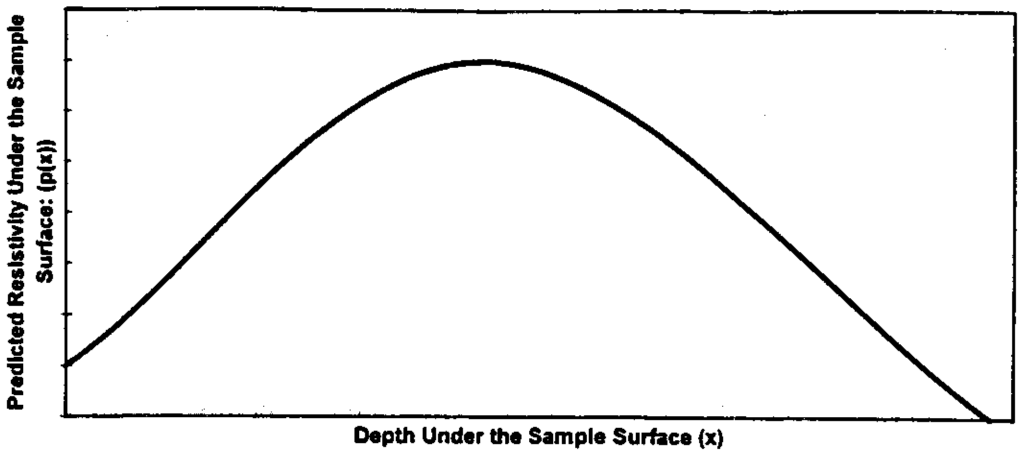

Figure 13. An Example of the Regression Results for the Assumed Resistivity - Depth Curve: $\rho(x) = ax^3 + bx^2 + cx + d$

Now, based on the previous discussion that the resulting curve ρ(x) is negatively proportional to the Stress-Depth curve, we can change the sign of the coefficients a, b, c and d to obtain a new curve, which should describe the actual Stress - Depth curve. Further, we change the scale of the y axis (based on the Stress - Depth curve obtained from the X-ray diffraction data) from "μΩ.cm" to "ksi" by arbitrarily setting the surface compressive stress for the Almen 003C sample to the same value as the X-ray diffraction data. With this scaling step, the function shown in Figure 14 is a good estimation of the true stress depth curve.

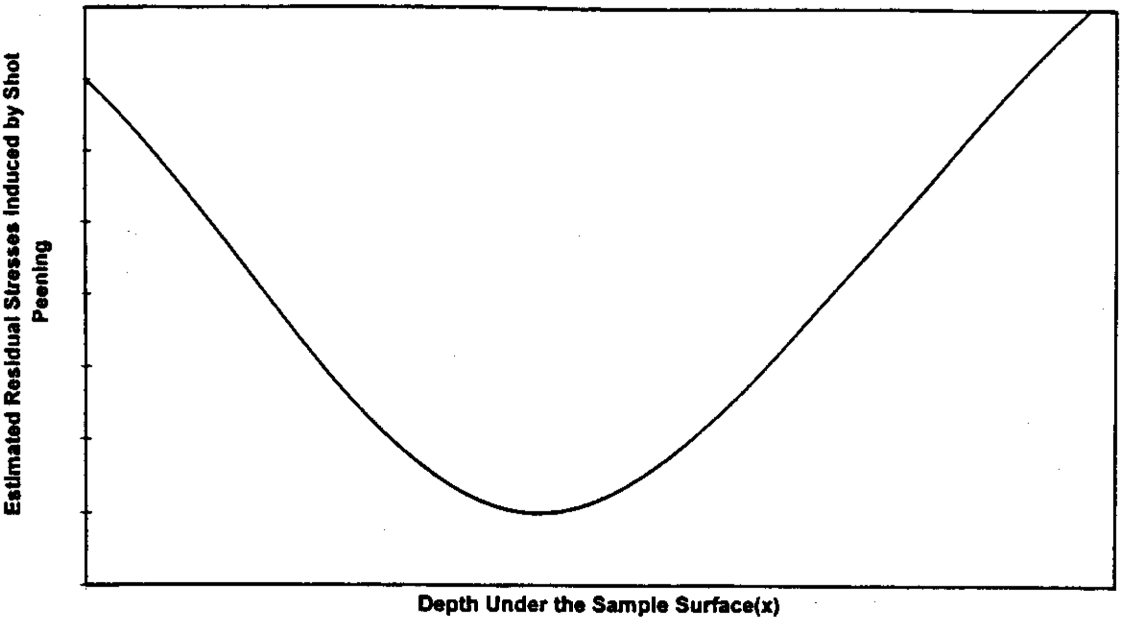

Figure 14. An Example of an Estimated Stress -- Depth Curve from Eddy Current Data

Using the eddy current results for Aluminum 7075 samples with known Almen intensities, we got the estimated results shown in Figure 15.

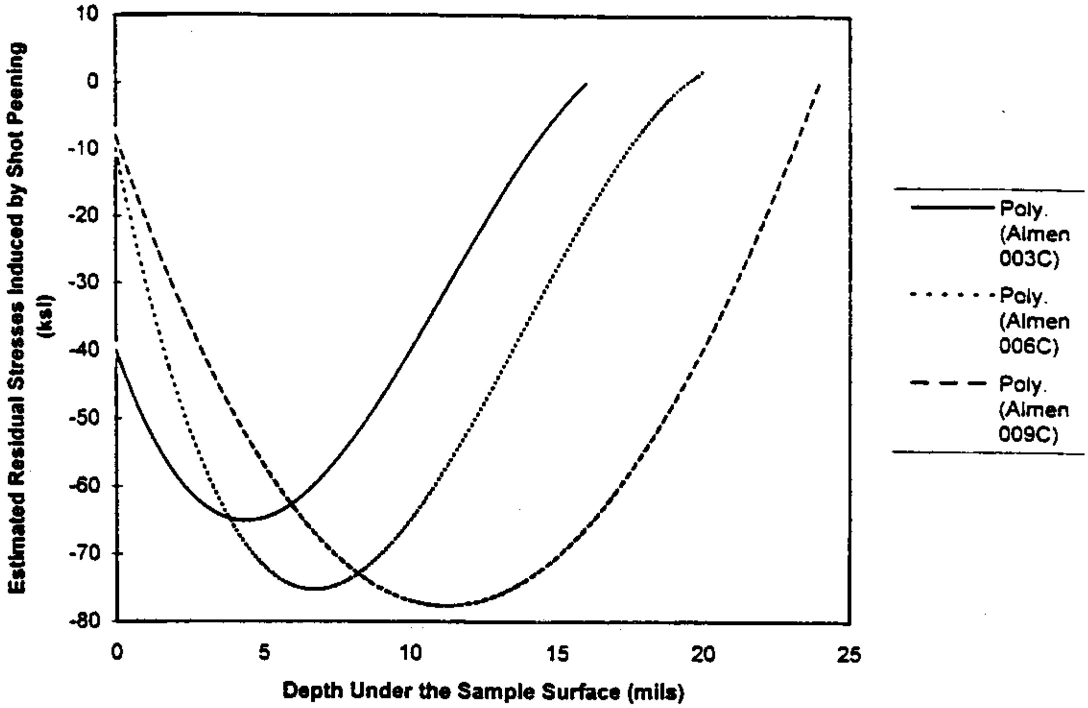

Figure 15. The Estimated Residual Stress -- Depth Curve Using Eddy Current data for Almen intensity 003C, 006C and 009C Aluminum 7075 Samples (y: stress (ksi). x: depth (mils))

Figure 15 shows that light shot peening results in big surface stress but with the peak stress occurring near the surface. Heavy shot peening results in a smaller surface residual stress but with the peak stress occurring deeper in the material. In short, we can conclude that the higher the shot peening intensity, the deeper the shot peening depth. In addition, the higher the shot peening intensity, the smaller the induced surface stresses. The maximum stress varies only slightly with shot peening intensity.

Figures 16 to 18 show the comparisons of Stress-Depth curves between X-ray diffraction data and eddy current data.

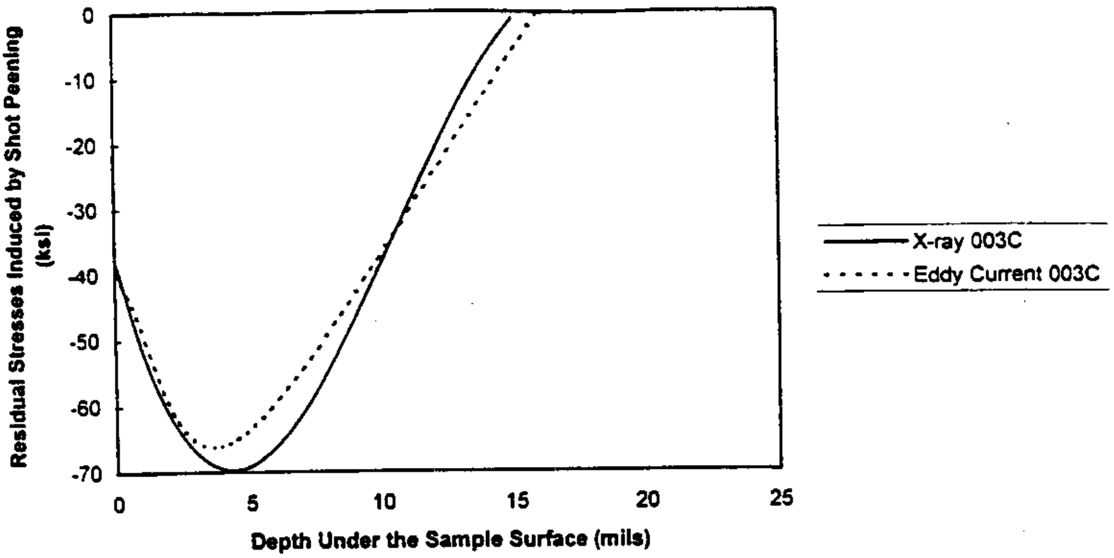

Figure 16. The Comparison of the X-ray Diffraction Results with the Eddy Current Results for Aluminum 7075 Peened to Almen 003C

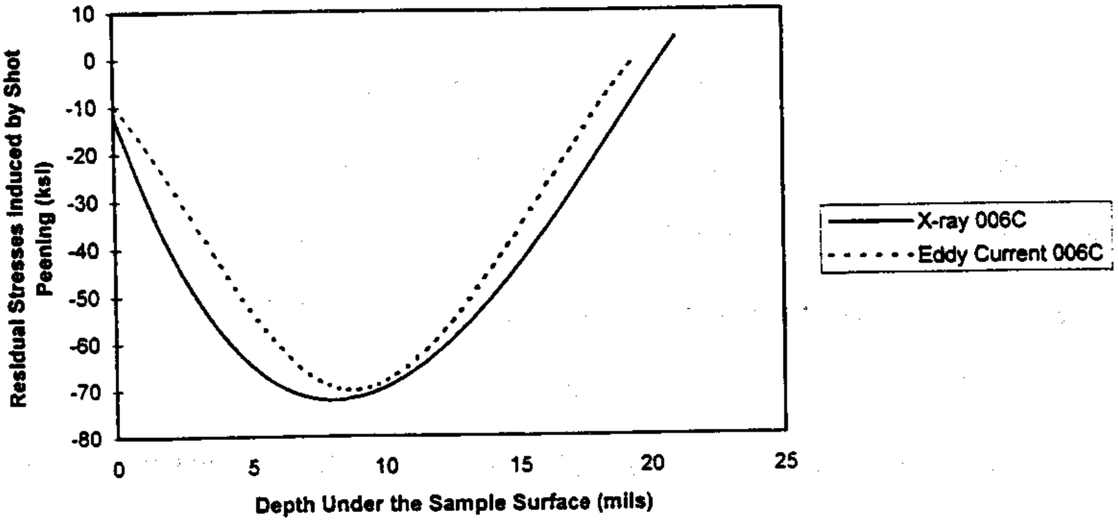

Figure 17. The Comparison of the X-ray Diffraction Results with the Eddy Current Results for Aluminum 7075 Peened to Almen 006C

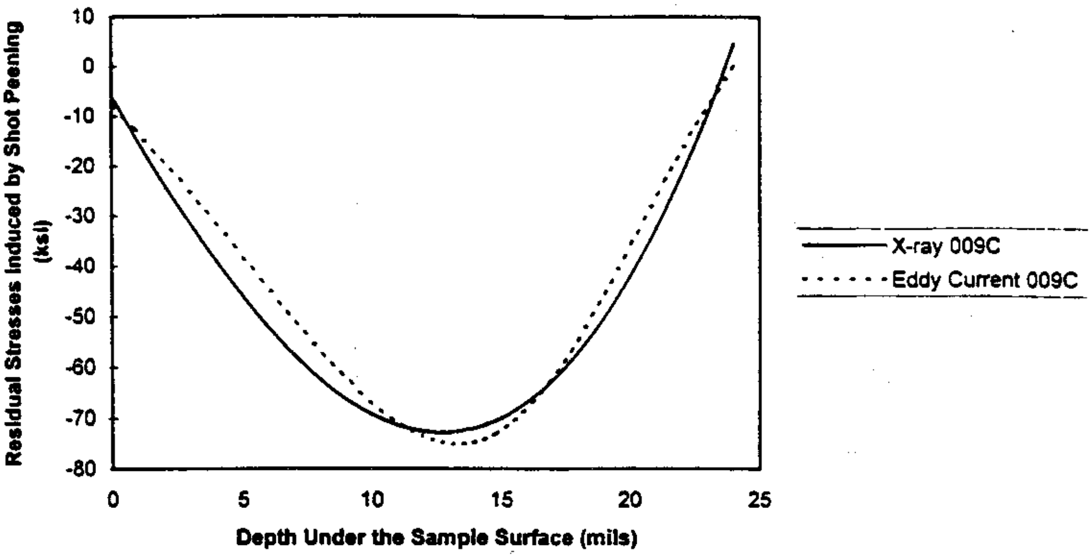

Figure 18. The Comparison of X-ray Diffraction Results with Eddy Current Results for Aluminum 7075 Peened to Almen 009C

Figures 16 to 18 show that the estimated Stress - Depth curves for shot peened Aluminum 7075 by using eddy current data are similar to that of the X-ray diffraction data. Note that the eddy current and X-ray curves coincide at the surface because they were forced to fit there. We conclude that the analytical model is successful and that the eddy current method can take the place of X-ray diffraction to estimate the Stress-Depth curve.

The same analytical process was applied for the samples with unknown Almen intensities, yielding the estimated stress-depth curves shown in Figures 19 and 20.

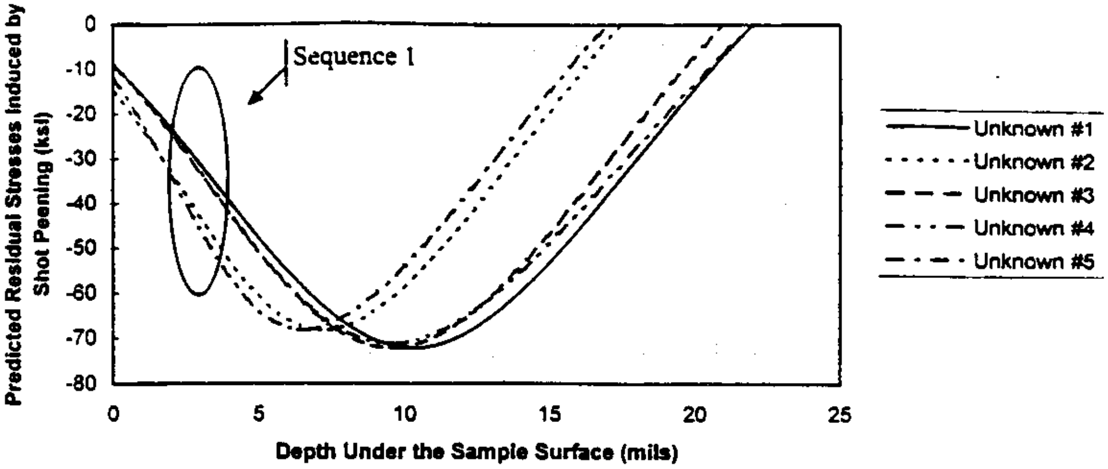

Figure 19. Estimated Residual Stress -- Depth Curve by Using Eddy Current Data for Aluminum 7075 Peened to Unknown Almen Intensities

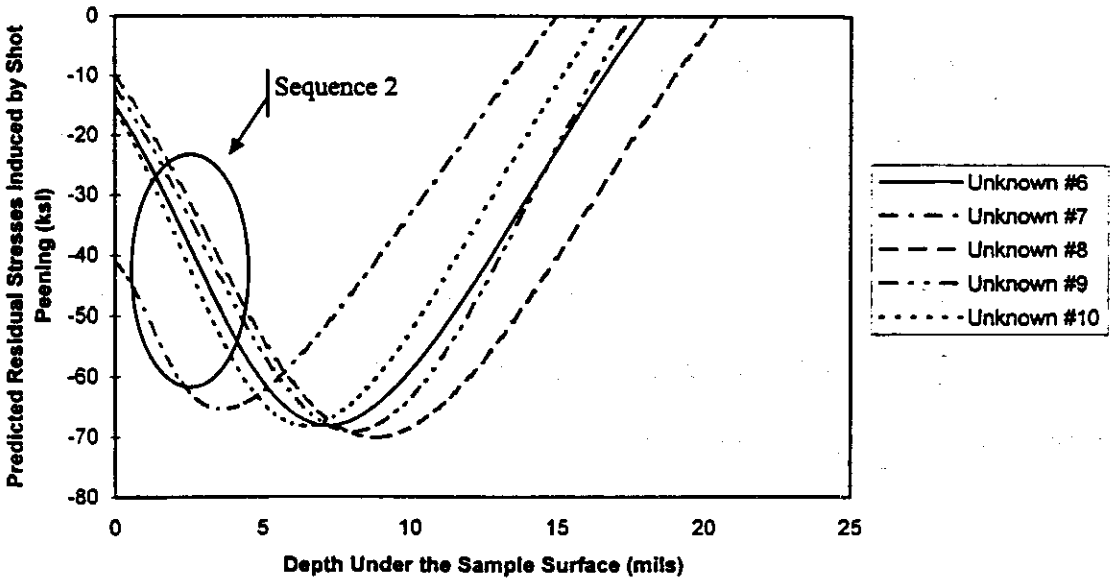

Figure 20. Estimated Residual Stress -- Depth Curve by Using Eddy Current Data for Aluminum 7075 Peened to Unknown Almen Intensities

Figures 19 and 20 show curves similar to the X-ray curves for known Almen intensity samples. We can conclude that:

1) The higher the shot peening intensity, the deeper the shot peening depth.

2) The higher the shot peening intensity, the smaller the surface residual stress. Notice that in Figures 19 and 20, the surface residual stress does not vary significantly when Almen intensity is above 0044 C, but the sequences 1 and 2 still follow this conclusion. In addition, X-ray diffraction results for known Almen intensities also indicated (see Figure 11) that the surface residual stress does not vary significantly when Almen intensity is above 003 C. This result is consistent with the industry experience that heavy shot peening (above 003C for aluminum alloy) does not give higher surface residual stress, but gives deeper shot peening depth. So if we want to get the high surface stress and the deep shot peening depth, we should apply heavy shot peening first on the sample to get the deeper shot peening depth, and then re-peen the sample with the light shot to get the higher surface stress.

3) All shot peening levels give about the same value of the maximum residual stress, although at different depths under the sample surface. The higher the shot peening intensity, the deeper the maximum stress occurs.

Conclusions

1. Eddy currents can be used as a non-destructive method to measure the residual stresses induced in non-magnetic materials by shot peening.

2. The eddy current testing system we have developed can measure the different Almen intensities for Ti6Al4V and Aluminum 7075 alloys quickly and without changing the test specimen in any way.
3. Measurement precision of ± 0.0004 Almen C units and measurement accuracy of ± 0.0003 - 0.0005 Almen C units have been demonstrated.
4. This eddy current testing system can estimate the Stress-Depth curve for Aluminum 7075 alloys.
5. Eddy currents have the potential to measure residual stresses in steel and other magnetic materials if the problems of variable magnetic permeability can be solved.
6. Eddy current testing is easy, fast and economic.