ADVANCES IN EDDY CURRENT MEASUREMENT OF RESIDUAL STRESS

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ABSTRACT

The high frequency eddy current response from a wide variety of common metals shows a unique signature for each sample, reflecting the particular distribution of residual stress in that sample. Individual samples are easily distinguished. A mathematical algorithm transforms the data gathered from the eddy current bridge into graphs that can be used to identify stress as a function of depth. Metals measured include aluminum, steel, titanium and several nickel-based alloys. Specific experiments demonstrate that the eddy current response is due to material stress and not other properties. Experiments in aluminum show the (reversible) effects of both tension and compression in elastically deformed samples.

KEYWORDS

Eddy Current, U.S. Patent #5898302,surface residual stress, flexible coils, mathematical algorithm, aluminum 7075,aircraft skins, aluminum 2024, EDM, steel 4140, standard depth of penetration, titanium 64, titanium 17, nickel based alloys, conductivity, non-destructive

I. At the Sixth International Conference on Shot Peening in San Francisco three years ago we reported that we had successfully compared the eddy current signatures of a number of aluminum and titanium samples and were able to unambiguously identify the intensity to which those samples had been peened. We used "standard samples", whose peening history was known, for comparison. We also mentioned briefly that we had been able to extend the technique to steel samples as well.

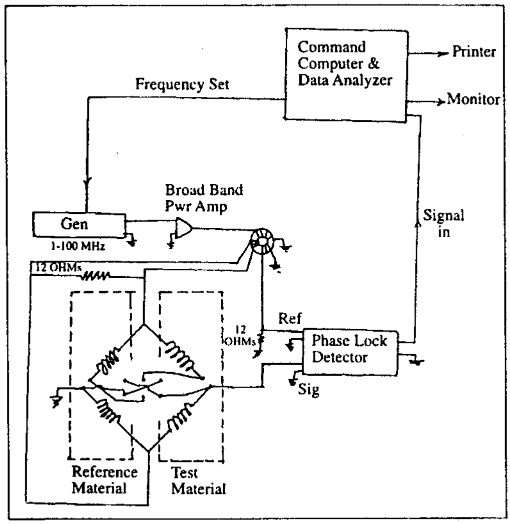

Fig. 1

Since that report we have not been idle. We have developoed an improved four-coil instrument (U.S. Pat #5898302) which greatly increases our sensitivity. See Figure 1. In addition, we typically take data over a wide sweep of frequencies. For aluminum the range of frequencies extends from 100 KHz to 10 MHz, which lets us examine the material within about .036 mm of the surface. In titanium our scans extend to 75 MHz corresponding to a depth of .06 mm. We believe we can scan to 100 MHz if necessary. In steel a scan to 75 MHz corresponds to the top .015 mm of the material. See Figure 2.

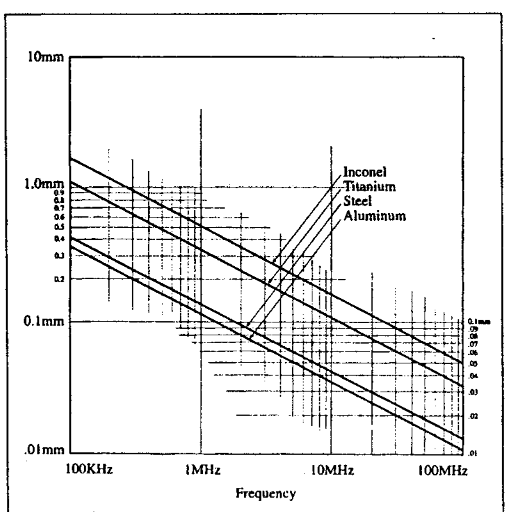

Fig. 2 Standard Depth of Penetration

The eddy current coils which we use are printed on a polyimide substrate and so are flexible enough to be adapted to fillets and other surfaces which are curved in one dimension. The high frequency coils are just a bit over 1.5 cm in diameter. Low frequency coils are about twice as large. We are experimenting with various ferrite configurations to reduce the coil size.

Recently, we have developed a mathematical algorithm which converts the raw eddy current data into a description of the actual conductivity of the sample as a function of depth. We do not have enough data or experience to determine how changes in residual stress affect the conductivity. In the descriptions which follow you will see the results of experiments which prove that residual stress does alter conductivity in a predictable fashion. So does reversible elastic stress. Furthermore, we will show evidence that both elastic tension and compression lower conductivity, though not similarly.

Finally, we shall show some examples of eddy current tests performed on commercial materials to confirm the presence or absence of residual stress.

II. In cooperation with the United Technologies Research Center we measured 17 samples of aluminum 7075 peened to various Almen intensities. A frequency scan from 100 KHz to 3.5MHz was chosen for these samples.

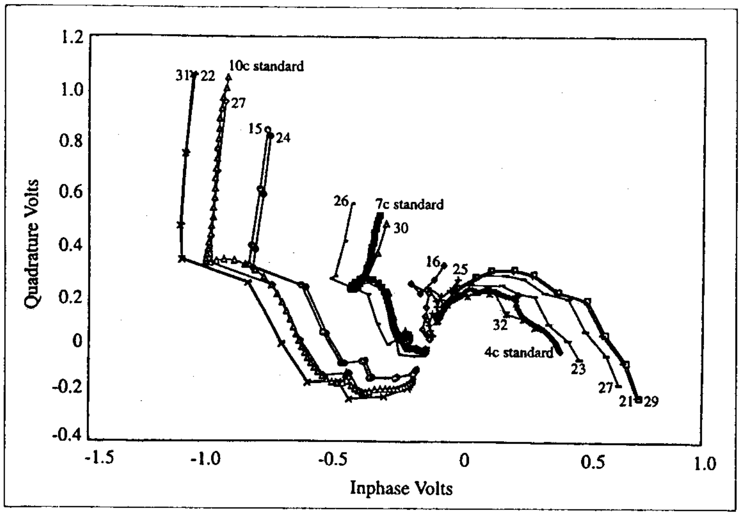

Fig. 3 Alum 7075, 17 examples various peening intensities. Samples 4ca, 7ca, 10ca x-rayed for standards.

Figure 3 shows a composite display of the eddy current results obtained with those samples. In general, lightly peened samples fall to the lower right of the diagram, more heavily peened samples are seen in the upper left region. A few samples appear to be nearly coincident, such as #21 and #29. Little information of engineering value can be gleaned from this composite figure although I might point out that individual data points are precisely reproducible, and even removing and replacing the test coils produces only a very small displacement of the measured point.

In Figure 4 we call attention to variations in the instrumental response from a given sample produced at various locations on the sample. These variations may be a combination of in-sample variations and of instrument variations due to the proximity of the test coils to one or more edges. Eddy currents circulate in the sample over a larger area than that of the coil, so we must remain aware of edge effects.

We compared the data from the UTRC samples to data from three samples of 7075 aluminum which were used several years ago in our work reported in 1996. The old samples, peened to 003C, 006C, and 009C were remeasured using the improved instrument and the results compared to three of the UTRC samples. That comparison is displayed in Figure 5. In each case the old samples, more lightly peened, are seen to appear to the left or counterclockwise to the UTRC samples which were more heavily peened. This result was puzzling until we were able to compare the x-ray results. The maximum stress in the old samples was much larger than in the UTRC samples in spite of a lower peening intensity. Subsequently, we learned that the peening conditions for the two sets of samples were totally different. The UTRC samples were peened to 200% coverage, using MI550 cast steel shot, while the old samples were peened to 100% coverage using MI230 shot.

We are in the process of applying the eddy current algorithm to this data with the expectation that the differences in residual stress will be much more apparent.

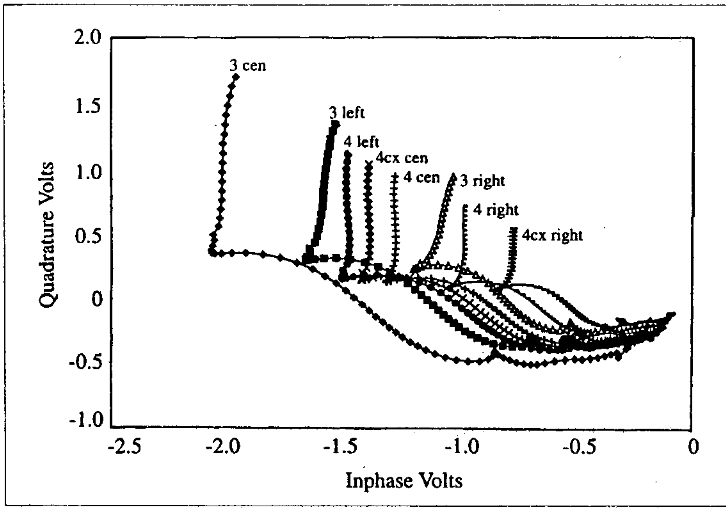

Fig. 4 In-sample variation of eddy current signatures.

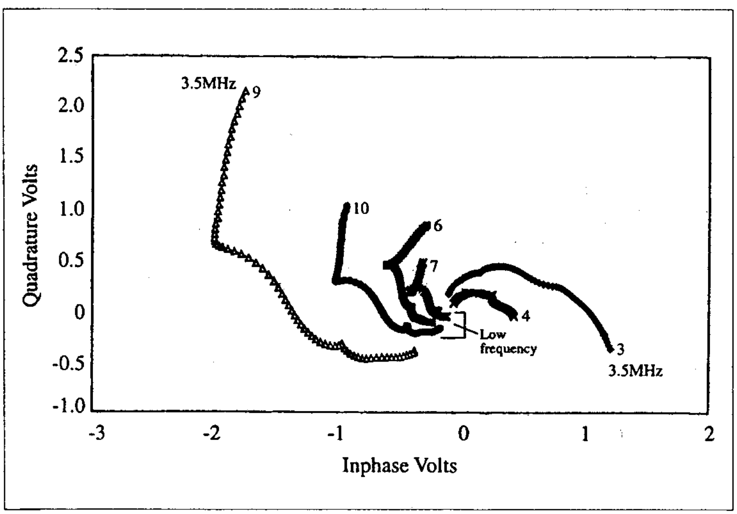

Fig. 5 Eddy current signatures of 6 samples which were x-rayed to verify stress distribution. Frequency range 100 KHz - 3.5 MHz.

III. Let us turn now to another group of aluminum samples. These are specimens of 2024 aluminum aircraft skins, about .6 mm thick, which have been soft peened with several different media, including Type V acrylic , polymedia Lite , and wheatstarch. Soft peening is a common method of removing paint which avoids the use of solvents. However,inspection of the surfaces shows that they are lightly dimpled and therefore probably carry a bit of residual stress. The samples are also slightly convex, curving away from the peened surface, further confirming that there exists a layer of residual stress. We were able to measure these specimens, both as received, and when held firmly against a flat surface. Figure 6 shows the eddy current signatures obtained from these samples.The residual stress in the surface was altered significantly when the samples were flexed.

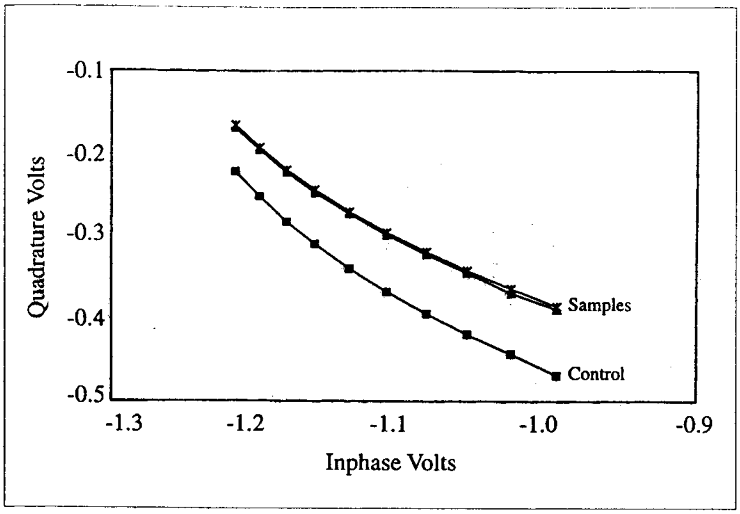

Fig. 6 Evidence of residual surface stress in soft-peened alum 2024, near 350 KHz.

IV. In an effort to quantify the effect which stress has on conductivity we prepared specimens of 6061 aluminum in the form of strips 1/8 thick and 2 wide. The strips were carefully annealed and then clamped to a fixture cut precisely to a radius of 48 . The resulting stress distribution in the sample is the well known linear function from a maximum tension on the outer surface to an equal compression on the inner surface. Eddy current coils were placed both above and below the plate so that both tension and compression could be observed simultaneously. We repeated the experiment for radii of 36 inches and 42 inches. We found that the annealed specimens of 6061 aluminum all tended to take on a permanent set of deformation which made the interpretation of the resulting data ambiguous. I include an example of those results in Figure 7 but no conclusions should be drawn from this example until it is corroborated by further work. We intend to repeat the experiments using examples of 2024T3 aluminum which are known to remain elastic over this range.

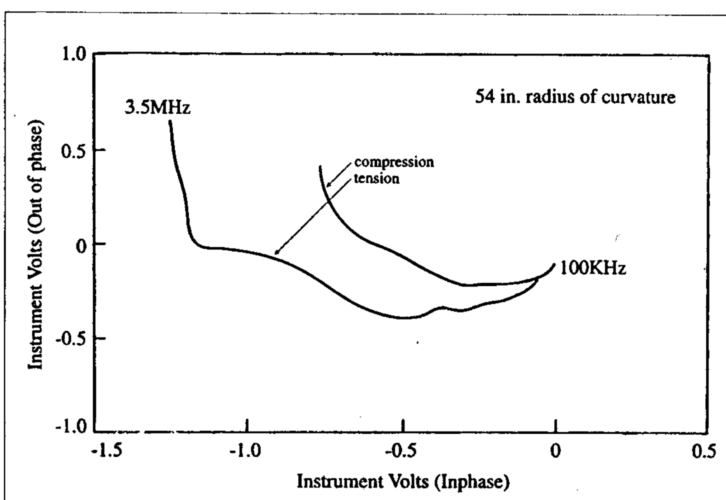

Fig. 7 Elastic stress in annealed smple @ 100 to 3500 KHz.

V. We performed a very important experiment on an old sample of 7075 aluminum that had been peened to 004C as part of Dr. Hong Chang's dissertation project. The sample was a 4 inches by 4 inches by 1/2 inch block of material which had been peened along two edges as shown in Figure 8. We remeasured the sample using our new bridge configuration and got the eddy current signatures seen in Figure 9. They are essentially similar to the curves seen earlier in Figure 4. After this measurement we carefully removed the top 1/16 inch of the sample using a wire EDM machine so that the peened and stressed layer was removed from the underlying supporting material. The thin samples were then cut again lengthwise to produce two peened and stressed plates and a center unpeened plate. The center plate remained flat while both of the peened plates curled noticeably. The stress in the peened plates was then measured and we observed that a large fraction of the stress had been removed. By multiplying the original eddy current data, taken before the surface was separated from the substrate, by a factor such as .55, .60, etc. we could get a near coincidence with the data taken after the top plates were removed and relaxed. See Figure 10. In a subsequent experiment the thin plates were firmly clamped to a flat substrate and the surface was again measured with the eddy current coils. All but a few percent of the original residual stress was restored. See Figure 11.

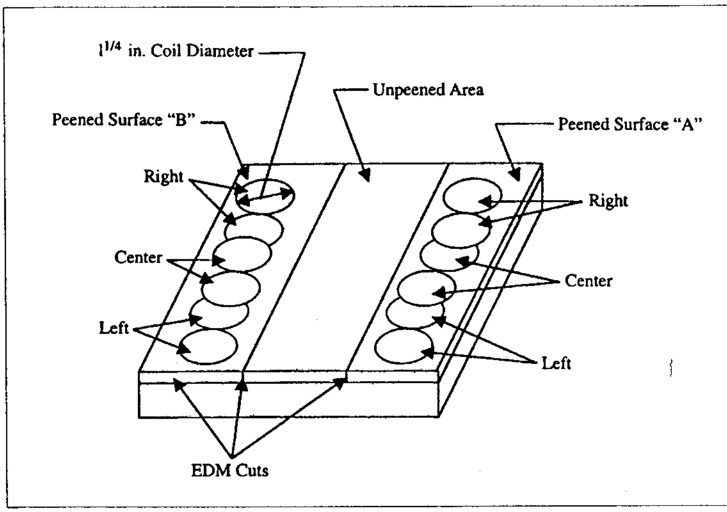

Fig. 8 Preparation of alum 7075 sample to confirm residual stress measurements.

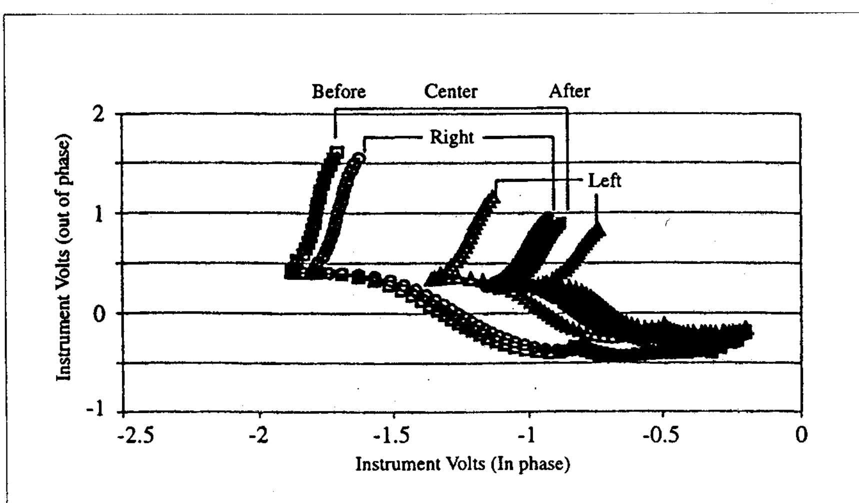

Fig. 9 Sample 5 — surface A Left, Center, Right - peened to 004c. Frequency range 100 to 3500 KHz.

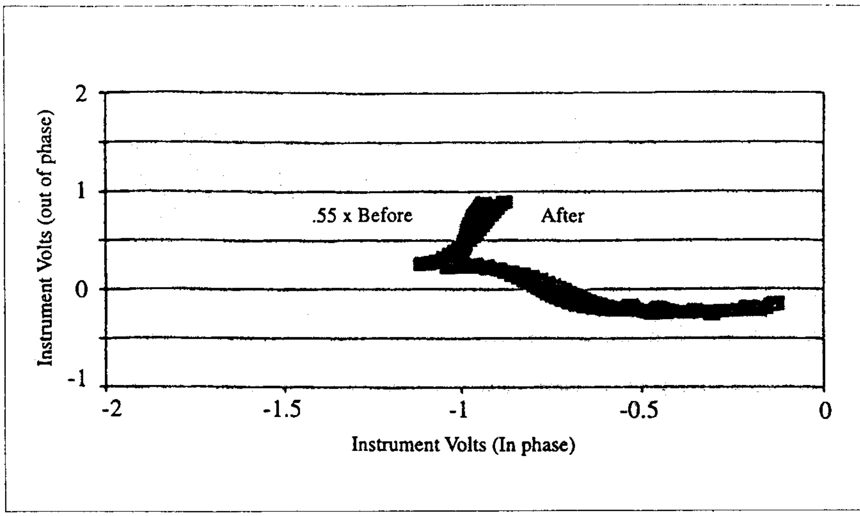

Fig. 10 Sample 5 — surface A Center - peened to 004c. Frequency Range 100 to 3500 KHz.

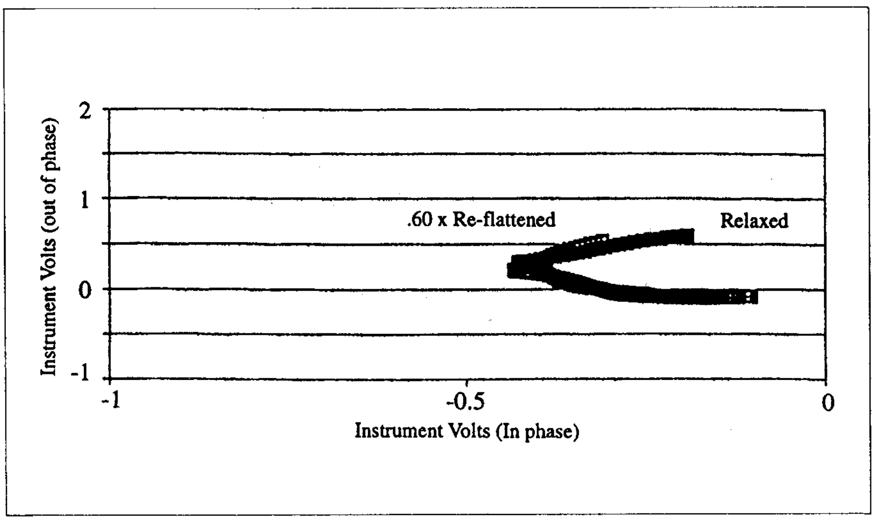

Fig. 11 Sample 5 — surface A Center - peened to 004c Re-flattened. Frequency Range 100 to 3500 KHz.

II. Turn now to Figure 12 which shows the eddy current response from 5 samples of 4140 steel leaf springs heat treated and shot peened at the Eaton Corporation. The parts were measured at 1 MHz intervals from 2 to 31 MHz. Samples D and E showed almost identical eddy current response, while samples A, B and C were markedly different. Near 31 MHz, which represents a standard depth of penetration in the material of .028 mm, the responses are all nearly the same, implying that the average conductivities in the material surfaces were very similar. X-ray data provided by Eaton reported residual compressive stress in the near surface region of about 90, 90, 65, 100, and 90 KSI respectivly for samples A through E. It was farther into the material that the residual stress curves diverged. Sample C in particular had much smaller residual stress up to a depth of 0.1 mm than any of the other samples, a fact obvious from the eddy current data.

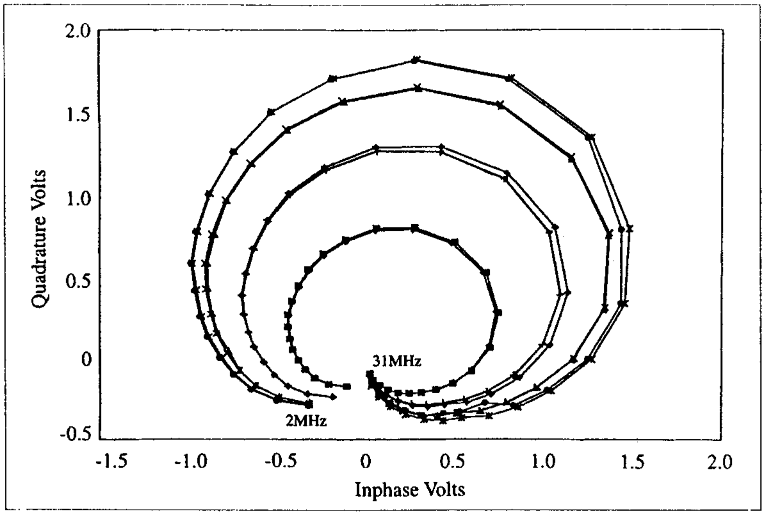

Fig. 12 Eddy current signatures of five 4140 steel samples peened to various intensities. Frequency range 2 to 31 MHz.

Figures 13 through 15 show the residual stress distribution as measured by x-ray diffraction.

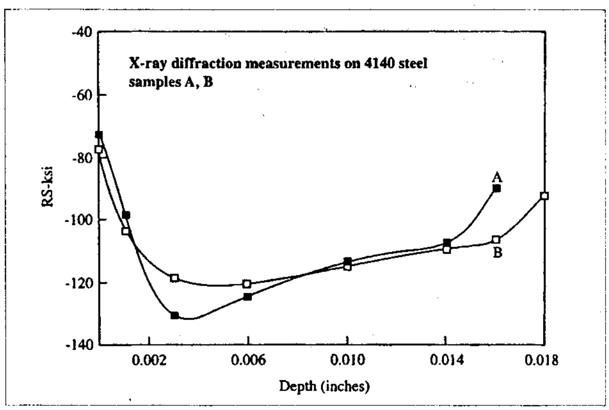

Fig. 13 X-ray diffraction measurements on 4140 steel samples A,B.

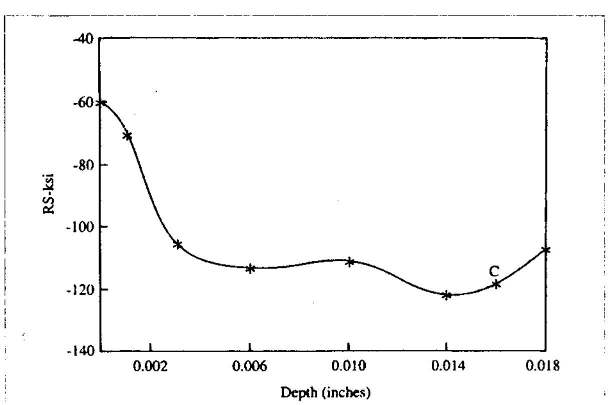

Fig. 14 X-ray diffraction measuremenhts on 4140 steel sample C.

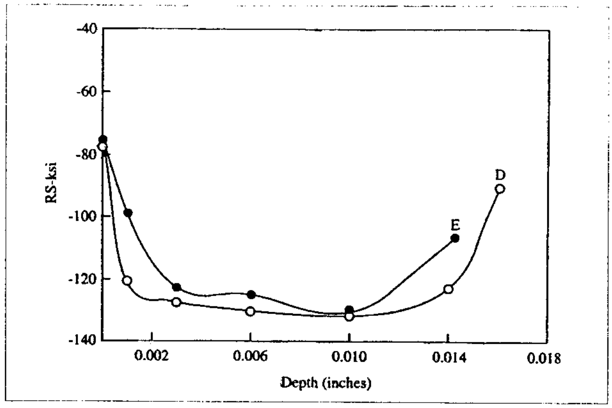

Fig. 15 X-ray diffraction measurements on 4140 steel samples D, E.

III. We have measured a number of samples of titanium 64 and titanium 17 provided by the General Electric Company. These samples were peened using a variety of peening parameters. Coverage, angle of incidence, intensity, etc. were varied. There is not time enough in this report to show the detailed correlation between eddy current signatures and peening parameters. Figure 16 summarizes our results and shows that each variation in peening parameters resulted in a noticeable change in the eddy current figure. Because of the poor conductivity of titanium our scans had to extend to 75 MHz, which still left us about .04 mm below the surface. In Figure 17 we apply our algorithm to one of the curves of Figure 16 to illustrate the simplification that can be achieved. Rather than plotting the change in circuit impedance caused by the eddy currents, using the frequency as a parameter, Figure 17 plots two new functions derived from the impedance data with the standard depth of penetration at that frequency as abscissa. These curves can be interpreted to reveal the conductivity (or stress) values in the sample as a function of depth.

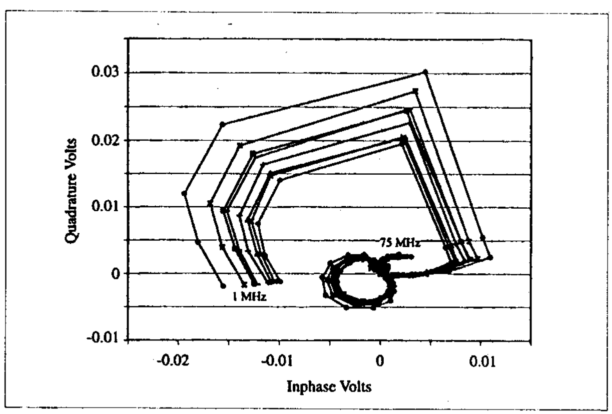

Fig. 16 Eddy current signatures of eight peened samples of Ti17. Frequency range 1-75 MHz.

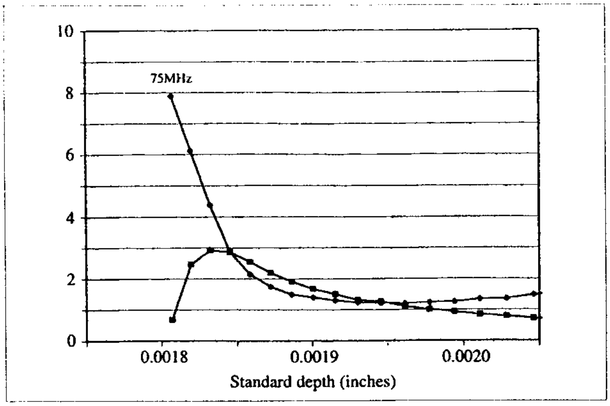

Fig. 17 Effect of data reduction algorithm on Ti17 eddy current signature.

General Electric also gave us several samples of peened nickel based alloys to measure. These alloys are even worse conductors than titanium and our highest frequency, 75 MHz penetrated to a depth of about .06 mm. Nevertheless, the eddy currents showed clear differences among the several samples.

Several facts should be emphasized in summarizing these results. Each point on the several diagrams we have shown was measured 10 times and the average value and statistical error recorded. A sample could be scanned repeatedly with identical results. If the probe coils were moved slightly, small differences in response were observed but those differences were much smaller than the sample-to-sample differences. A complete scan of one location on a typical sample takes about a minute, and is, of course, absolutely non-destructive. Because of the quality of the data several derivatives of the data can be taken before the scatter becomes objectionable.

We have, after much effort, developed a mathematical algorithm for converting the eddy current data into functions which can be directly interpreted for surface stress, maximum stress, etc. It should be kept in mind that our experiments measure conductivity and that the residual stress which alters the conductivity is not directly measured. In fact, the actual relation between stress and conductivity is unknown, except for our brief experiment with elastic deformation of aluminum 2024. We will continue to try to get more precise information about the conductivity-stress function in future experiments, particularly, in other metals than aluminum. Meanwhile, we know that there exists a simple correlation between stress and conductivity which permits non-destructive verification of shot peen induced residual stress in any of the common metals.

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