COMPARISONS OF THE BEHAVIOR OF REAL AND IMAGINARY RELUCTANCES BETWEEN SAMPLES OF 6061 ALUMINUM AS A FUNCTION OF GRAIN SIZE

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INTRODUCTION

Relative measurements of real and imaginary reluctances were made as a function of sample thickness on both rolled and cast 6061 aluminum samples using an ac magnetic bridge. Samples were both nonannealed and annealed. Evidence was developed that the imaginary reluctance (which is shown here to respond to the conductivity of samples) responds more to the bulk properties of the samples while real reluctance apparently responds more to surface conditions such as surface residual stress.

Measurements were made through the use of a modified ac magnetic bridge. This bridge incorporates a copper insert between each set of four gaps. The insert separates the poles of the individual gaps and serves to force the electromagnetic field into a sample juxtaposed to one gap face (called here the "x" gap). The "y" gap is the gap in the balancing arm of the bridge and, in these experiments, has no sample. Therefore, the measurements were made relative to an empty bridge gap. They are, therefore, referred to here as "relative" measurements. To convert a relative real-reluctance measurement to absolute real-reluctance measurement, the real reluctance of the y gap (the empty gap) must be subtracted from the measured relative value with the sample in the x gap. Zinke and Schmidt [1] have shown how to determine the reluctance of an empty gap. Since the imaginary reluctance of the gap depends on the conductance of the sample in the gap and an empty gap has no conductance, the relative imaginary reluctance can be taken to be equal to the absolute imaginary reluctance. Since nondestructive-evaluation measurements are typically comparative, relative real-reluctance measurements are as effective in evaluating samples as absolute measurements would be and are a good deal easier to obtain. Therefore, relative real-reluctance measurements are presented here.

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Schmidt and Zinke [2] have previously shown that for samples of 2024 aluminum above 350 hz the relative imaginary (I_m) reluctances can be expressed in the general form

$$I_m = A\left(1-e^{\left(-\frac{x}{\delta}\right)}\right). \tag{1}$$

where x is the thickness of the sample, A is an amplitude, and δ is the skin depth. It was clear from previous work [2] that this formula did not apply at 200 hz and below. Although the curves in this range had an appearance similar to Equation 1, they could not be made to match the curve of Equation 1 exactly, and the skin depths which were calculated were less than those for pure aluminum, which certainly could not be true. The work here was done at 200 hz, and Equation 1 will be used here simply to calculate and compare the amplitudes A of various samples while recognizing that this procedure is approximate.

THE EXPERIMENT

The original intent was to produce a coherent set of 6061 aluminum samples ranging in thickness from about 0.5 mm to about 12 mm and to make thickness, frequency, and lift-off studies. A set of 7 samples were acquired from commercially-available, rolled, 6061 aluminum. These pieces were sheared into 10-cm square coupons from larger sheets and were 0.48, 0.79, 1.22, 1.96, 2.49, 3.09 and 4.01-millimeters thick respectively. A second set of samples was milled from 12.7-millimeter cast 6061 stock. This stock was milled into thicknesses of 3.96, 4.57, 5.03, 6.12, 7.65, 8.89, 10.16, 11.46 and 12.68 millimeters. Early reluctance measurements showed a clear difference between the two groups of samples and further investigation showed that the milled samples had a grain structure which was much coarser than the rolled. Later, another 9 samples were milled from the cast aluminum for direct comparison in the same thickness range with the rolled aluminum. These samples were milled to thicknesses of 0.85, 1.12, 1.84, 2.39, 3.10, 3.96, 4.55, 5.13 and 6.10 millimeters. The milled samples were also 10-cm square. The rolled samples and the thicker set of cast samples were subsequently annealed.

The bridge used to examine the samples in these experiments was the same bridge used in Reference 1 and is described more or less exactly by Schmidt, Zinke, and Nasrazadani [3]. The general geometery of the bridge can be seen in Reference 2. The gaps of this type of modified ac magnetic bridge are separated by a piece of copper which produces a convenient geometry into which to place the sample [4]. In practice, this piece of copper is inserted between two halves of the bridge structure. In these experiments (as well as those of Reference 1) this insert was 1.07 millimeters thick. The bridge was driven by 12 amp-turns (as in Reference 2). Coils are wound around the arms of the bridge which contain gaps x and y. Resistances (R) and capacitances (C) are attached in parallel to these coils. These resistances and capacitances are varied to balance (or null) the bridge to output values of less than 1 microvolt. (Typically, unbalanced outputs are 8-10 millivolts). Most of the data were obtained at 200 Hz which was selected for maximum penetration of the samples. The voltage output of the bridge was read by a Hewlett Packard 3582A Wave Analyzer set to this frequency. The purpose of using this device is to eliminate harmonics in the null signal. Therefore, the wave analyzer was used as a bandpass filter. Harmonics can be present in the driving signal and are also generated by magnetic circuits. In either case, they usually produce a voltage which is much greater than and masks the 1 microvolt demanded for null. Therefore, the harmonics must be filtered out.

The experiment was performed by initially placing the bridge on a thick piece of plastic to isolate it from any surrounding metals. Under these circumstances, both the x gap and the y gap are empty of any material with conductivity/permeability. The bridge is nulled, and the value of C (either C_x or C_y) and of R (either R_x or R_y) are recorded. A value for infinity was recorded for the resistance of the empty null coil in Equation 2 below, and a value of zero was recorded for the empty null coil for the value of C in Equation 3 below.

The bridge was then placed with the x gap in the center of the sample but separated from the sample by a piece of plastic 0.25 millimeters thick to establish lift off, and the bridge was nulled to obtain the values of C_s (either C_{sx} or C_{sy}) and R_s (either R_{sx} or R_{sy}). The same substitutions for infinity and zero for resistances and capacitances of the empty null coils were made. From Zinke and Schmidt [5], the real and imaginary reluctances are respectively related to these resistance and capacitance values through the following equations:

$$I_m - N^2\omega\left[\left(\frac{1}{R_{sx}}-\frac{1}{R_x}\right)-\left(\frac{1}{R_{sy}}-\frac{1}{R_y}\right)\right], \qquad \text{and} \qquad (2)$$

$$R_e - N^2\omega^2\left[(C_{sy}-C_y)-(C_{sx}-C_x)\right]. \qquad (3)$$

RESULTS

Comparisons between the real and imaginary reluctances of the rolled and cast samples in the same thickness range are shown in Figure 1. The curve of Equation 1 is matched to the measured imaginary reluctances by a least squares technique. The Equation 1 results are shown as dashed lines. The least-squares technique yielded an amplitude value (A) for the rolled sample of 1.09 and for the cast sample of 0.925.

This difference can be evaluated in terms of the conductivity by modifying the imaginary-reluctance term above for a solid sample rather than a resistance attached to a coil. If the magnetic flux intersects a solid sample rather than a coil, the number of turns N can be considered to be 1. The imaginary reluctance now takes the form

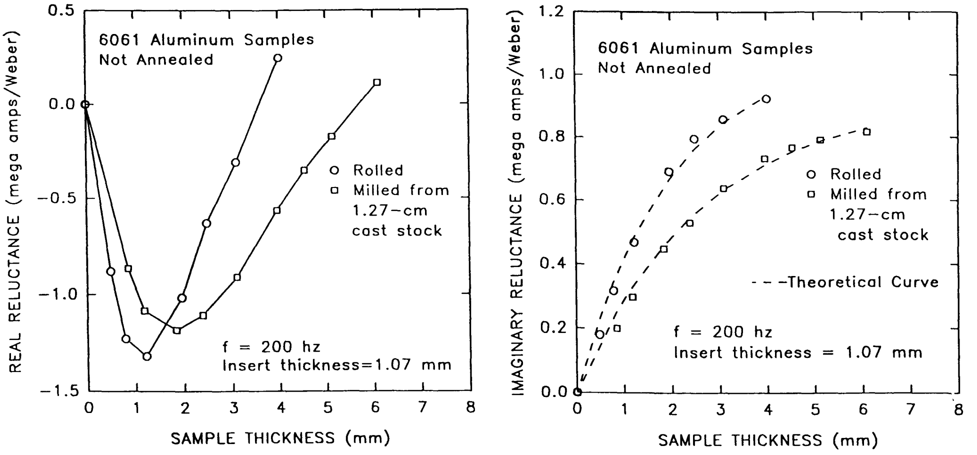
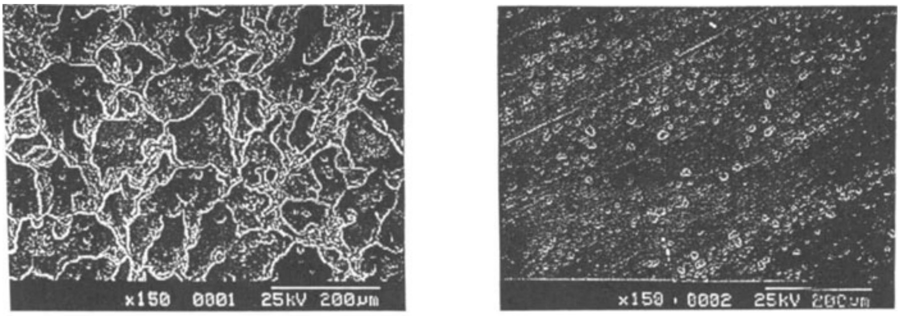


Figure 1. Real and imaginary-reluctance comparisons of cast and rolled aluminum samples.



Cast Aluminum Sample

Rolled Aluminum Sample

Figure 2. SEM of Aluminum Samples.

$$I_m = -\frac{\omega}{R}. \tag{4}$$

The resistance R can be expressed as $R = \frac{L}{\sigma A}$ where A represents the area of some sort of extended current path of some average length L in the solid sample and σ is the conductivity of the metal. Where only small changes are made in the experimental conditions, we can substitute a geometrical factor G for L/A, and the above equation becomes

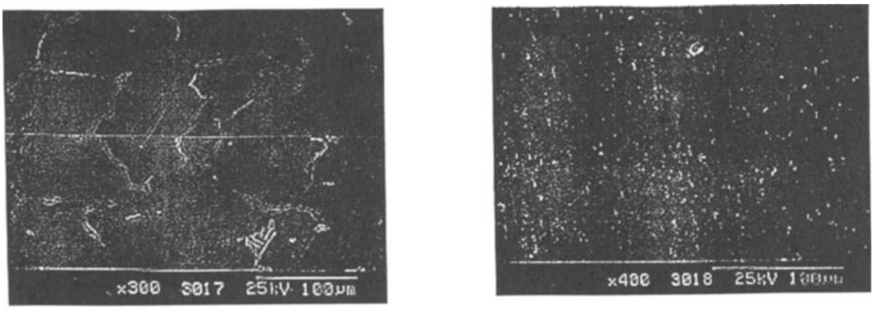
$$I_m = -\frac{\sigma\omega}{G}. \tag{5}$$

Therefore,

$$\frac{\Delta\sigma}{\sigma} = \frac{\Delta I_m}{I_m}.$$

From Equation 5, it is apparent that the rolled sample has a conductivity which is approximately 16 percent higher than the cast sample.

Figure 2 shows the SEM images for two samples, one rolled and one cast, having the same thickness in the condition used for the bridge measurements. The larger grain size for the cast aluminum is very obvious in the figure. Figure 3 shows the same surfaces after polishing. For the cast aluminum there are a large number of microcracks in the material. Note that the white material in the photographs is residual polishing compound which penetrated the surface cracks. These microcracks would reduce the conductivity of the material as outlined in the previous discussion. The effect of the microcracks on the measured reluctances is illustrated in Figure 1. The imaginary reluctance is reduced for the cast samples which would be expected based on the number of flaws in the material.



Cast Aluminum Sample

Rolled Aluminum Sample

Figure 3. SEM of Polished Aluminum Samples.

The variation of the relative real reluctance with sample thickness, an example of which is seen in Figure 1, is simply not well understood. In the sample gap of the bridge, a lift-off space exists and the effect of Lenz's Law in the sample forces a portion of the net flux into this space. Either increases in frequency or increases in sample thickness would seem to have a tendency to increase the Lenz's Law effect. Both in Reference 2 and here it is apparent that there is clearly a real-reluctance minimum, and here the minimum is clearly a function of the conductivity of the samples, the thickness of the samples, and the frequency at which the samples are examined. The imaginary reluctance varies throughout the region where the real reluctance exhibits the minima so that from an NDE point of view, these regions represent an opportunity to examine specific aspects of problems associated with small variations of conductance with radiation damage, work hardening, and the like. Another puzzling aspect of the interaction of electromagnetic fields produced by gaps with inserts is seen in the work on 2024 aluminum in Reference 2 where the total relative reluctance was seen to be essentially constant with lift off over a range from 0.1 to 0.6 millimeters.

As stated previously, the original intent was to produce a coherent set of 6061 aluminum samples ranging in thickness from about 0.5 mm to about 12 mm for studies of effects of lift off, frequency, insert thickness, and the like. The samples which were to be used for this set were the rolled samples and the thicker milled samples. The results of the initial measurements on these two sets of samples, shown in Figure 4, immediately indicated the basic difference between the sets. The thicker (milled) set was found to be of cast aluminum, and the SEM data of Figures 2 and 3 showed the microscopic differences which accounted for the differences in the reluctance measurements. The two sets of samples were annealed and the results of the annealing attempts are shown in Figures 5 and 6.

The protocol for annealing was determined on the basis of measured change or lack thereof as the annealing process continued. First the samples were annealed at 350° F for 27 hours in 9-hour increments and measurements made after each increment. Little change was seen. Then the temperature was raised to 533°F, and annealing took place for 9 hours. Some change was noted. Finally, the temperature was raised to 703°F and the samples were treated for 9 hours. In all cases, the cooling was done by turning the furnace off and letting the furnace temperature return to ambient. The curves resulting from measurements at the end of the first 36 hours and then 45 hours are labelled as B and C on Figures 5 and 6.

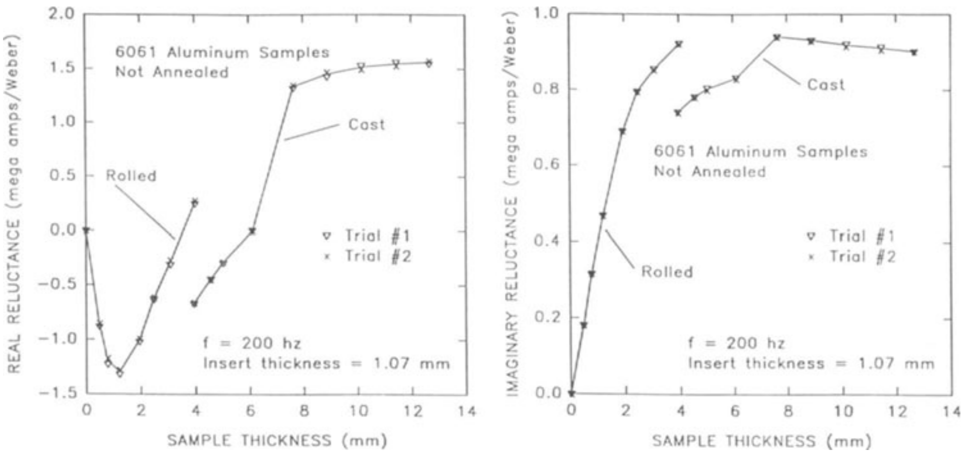


Figure 4. Real and imaginary-reluctance comparison of a series of thin rolled samples with a series of thicker cast aluminum samples.

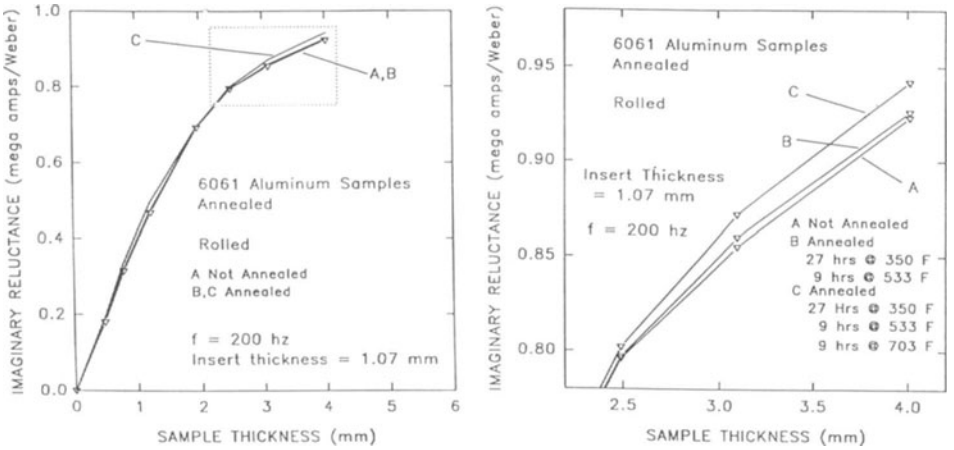


Figure 5. Imaginary-reluctance comparison of rolled aluminum samples before and after annealing.

The response of the imaginary reluctance of the rolled samples to annealing is shown in Figure 5. The percentage increases in the conductance for samples approximately 3 mm thick are calculated from the changes in imaginary reluctance to be 0.6 percent from protocol B and 1.7 percent from protocol C. It is clear that annealing made greater changes in samples of greater thickness. These are average changes of the bulk thickness of the plate which must have regions of residual stress on both surfaces.

The responses of the reluctances of the cast samples to annealing are shown in Figure 6. Variations from sample to sample in this subset would be expected because of the possible microscopic variations in the sample in the region where the measurements were made (the center of the 10 cm by 10 cm sample). Therefore, these curves can be expected to be more irregular than those of the rolled samples, and they are. In the imaginary-reluctance curves of Figure 6, some effects of annealing are seen between the 4 and 6 millimeter-thick samples, but the rest of the samples show no consistent behavior. It may be of some interest that the largest changes in conductivity occur from the effects of protocol B, i.e., the initial annealing. The same large changes from protocol B are seen in the real-reluctance curves, where the absolute changes are much larger than for the imaginary-reluctance curves. Moreover, the real reluctance exhibits this large change throughout the entire range of sample thicknesses from 4 to 12 millimeters. If the real reluctance change resulted from some sort of increase of bulk conductivity in the sample which forced the resultant flux into the lift-off space, then large and consistent changes should have also been seen throughout the imaginary-reluctance curve. A possible explanation of the observations is that surface stress was introduced in the milling of these samples, and what is seen here is stress relief from the initial (or B) annealing protocol. This explanation is consistent with the fact that the larger changes in imaginary reluctance are seen in the thinner samples where surface stress would constitute a larger fraction of the bulk of the sample.

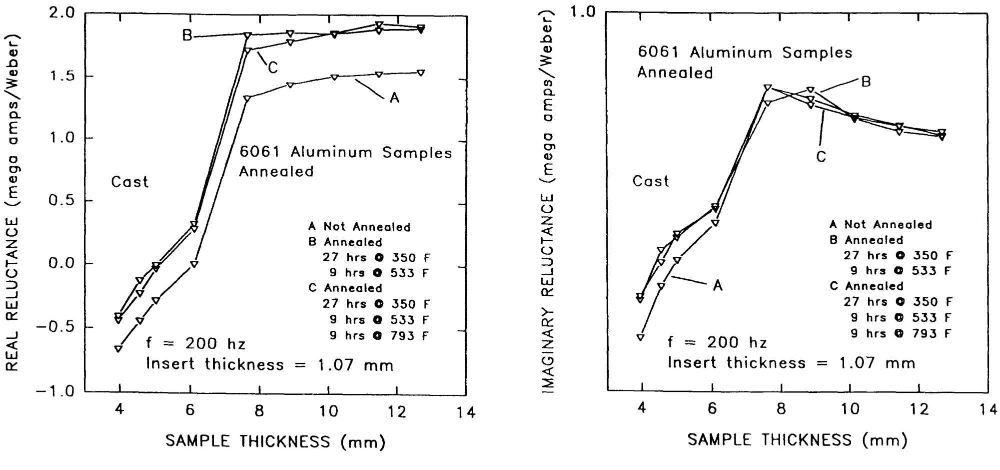


Figure 6. Real and imaginary-reluctance comparison of cast aluminum samples before and after annealing.

CONCLUSIONS

The results show that the a-c magnetic bridge can easily detect differences in microstructure of various samples. Imaginary reluctance changes are more sensitive to the bulk properties of the material while the real reluctance tends to provide a measure of the surface properties. This capability to distinguish may be of use in material process control and material feed lines for various manufacturing operations.

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