

REPORT ON ELECTRICAL CONDUCTIVITY IN HEAT TREATED ALUMINUM ALLOY PLATE



The Aluminum Association
Incorporated
900 19th Street, N.W., Washington, D.C. 20006



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ABSTRACT

This paper discusses the value and the limitations of using electrical conductivity for monitoring the strength of aluminum alloy plate. The variation of conductivity and mechanical properties with quench rate is detailed and the process for distinguishing metal with a marginal quench from metal with a good quench is described.

The factors which influence conductivity other than quench rates are also discussed. These factors include lot-to-lot variations in chemistry and laboratory-to-laboratory variations in test methods and test equipment. Because of these variations, it is concluded that conductivity is an excellent tool for in-process quality control where one operator using one instrument can check the conductivity of one piece of plate for differences which may indicate differences in quench rate. It is not, however, an effective acceptance test because of the large errors which can be introduced into the measurements. The final referee for metal integrity must remain the mechanical property tests.

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INTRODUCTION

In recent years the aircraft industry has made significant strides to improve the integrity of its aircraft by improved methods of monitoring the quality of aluminum plate. One relatively common method used for this monitoring is electrical conductivity as measured with an eddy current instrument. While the metallurgical mechanisms involved in solution heat-treated plate are well documented and understood¹⁻¹², caution must be exercised with respect to attempts to establish direct correlations between metallurgical characteristics and conductivity values. Although electrical conductivity measurements are useful, there are limitations to their precision and accuracy. This paper describes the experiences of aluminum producers with electrical conductivity and attempts to illustrate its usefulness as well as its limitations.

Electrical Conductivity Measurements by Eddy Currents

In the eddy current method of determining conductivity, the conductivity meter generates a high frequency alternating current which is passed through a coil in the probe. When this probe is placed on a piece of metal, secondary or eddy currents are formed in the metal to a depth of about 0.030 to 0.100", depending upon the characteristics of the metal and the meter being used. For a steady state condition, the eddy currents formed are a function of the metal's conductivity. The eddy current in the metal generates its own electro-magnetic field which acts on the field of the probe producing a change in the electrical characteristics of the coil circuit. The magnitude of this voltage change can be measured by the meter and indicates the near surface conductivity of the metal. The conductivity is usually expressed as a percentage of the 100% conductivity on the International Annealed Copper Standard (% IACS).

When alloying elements are added to aluminum they can have widely differing effects on electrical conductivity depending upon whether they are in or out of solid solution. When alloying elements are in solid solution, their effect on electrical conductivity is significant. Many of the non-strengthening elements such as vanadium, chromium, manganese and titanium have a dramatic effect on conductivity with little or no contribution to strength (Figure 1).¹³ When alloying elements are out of solution (i.e., in discrete second phase constituents) their effect on electrical conductivity is much smaller, sometimes reduced by as much as a factor of 10.¹⁴ Any thermal operation may affect the amount of dissolved elements in a plate and change the conductivity. In this manner, electrical conductivity measurements are useful for following changes in the amount of solute in solid solution through the quenching and aging processes. (Conductivity is, however, affected by other factors such as measurement errors, and these will be discussed in later sections.) The following section discusses the two main uses of conductivity, as a quality control tool in monitoring quench performance and in monitoring aging for corrosion resistant tempers.

Applications of Electrical Conductivity as a Quality Assurance Tool

Monitoring Quench Performance

During solution heat treatment, the various soluble elements in an alloy dissolve into solid solution. Quenching retains these elements in a supersaturated solid solution provided the quenching is rapid enough to prevent diffusion and precipitation. The temperature range where quench rate is critical is approximately 750 °F-550 °F for most alloys (Figure 2).¹⁵ Above this range the super-saturation is too small to be of importance

and below this range the diffusion rate becomes insignificant. If the quench rate is not fast enough to prevent precipitation, then whatever solution precipitates during the quench will be in the form of coarse, non-homogeneous particles and will be unavailable for strengthening. The only correction for this situation is reheat treatment.

In general, a faster quench rate will produce a lower conductivity than a slower quench rate. However, the degree of change in conductivity depends on the quench sensitivity of the alloy. Figure 3 shows three different alloys and the changes in their conductivity with varying quench rates.¹⁶ Alloy 6061 (Al-Mg-Si) shows very little change in the conductivity over a wide range of quench rates. On the other hand, 2024 (Al-Cu-Mg) and 7075 (Al-Zn-Mg-Cu) both show a significant degree of quench sensitivity over a wide range of quench rates. Therefore, if either the 2024 or the 7075 had a large variation in quench rate within a plate it would be detectable. The quench rates normally experienced in plate are from 10-100°F/second over the critical temperature range of 750°F-550°F. The effect of quench rate on yield strength is shown in Figure 4.¹⁷

To use conductivity to detect a variation in quench rate, it is desirable to allow enough time to lapse after quenching for the W-temper conductivity of the plate to stabilize (Figure 5).¹⁸ This minimizes natural aging time as a variable. However, since processing of a plate in a mill may take up to several weeks, it is desirable to measure electrical conductivity in the freshly quenched W-temper. In this manner any problems with a quench system or practice can be promptly detected and corrected. It would be desirable to develop a correlation between W-temper electrical conductivity and T-temper properties that would assure a given W-temper conductivity would meet final properties. However, because of many variables in measurement, conductivity values are imprecise numbers. As a result, the correlation developed (Figure 6)¹⁹ is also imprecise. The spread of the data precludes the establishment of an absolute value for an acceptable conductivity. By using a conservative number for W-temper an early warning system can be established to prevent marginal metal from being processed.

The second and perhaps most valuable use (considering current quench design) is to check the uniformity of the quench rate. The many variables which affect conductivity are minimized by having one operator use one instrument to measure the conductivity in several locations on one plate. A large difference in conductivity serves as a flag that further metallurgical evaluation is necessary.

Conductivity for Monitoring of Aging

When an alloy is aged after being solution heat-treated, the alloying elements in solution are precipitated out and electrical conductivity is increased. This makes it possible to monitor the aging process by measuring electrical conductivity. Advantage is taken of this when improved corrosion resistance is desired as in the T7-temper. It is possible to verify that the correct degree of aging is achieved by using electrical conductivity measurements in conjunction with mechanical properties. This assumes that the conductivity of a plate of a given alloy is primarily effected by the aging operation.

Limitations of the Correlation Between Conductivity and Mechanical Properties

Since electrical conductivity is helpful for in-process monitoring and for indication of corrosion resistance, it is logical to attempt to use it for verification of mechanical properties. Figure 7 shows a yield strength vs. conductivity plot for lots of 7075 with a variety of quench rates.²⁰ For a given conductivity measurement, the width of the 95% confidence band about the regression line is approximately 18 ksi. This generates a high degree of uncertainty when one attempts to predict mechanical properties from electrical conductivity.

Reasons for the poor correlation fall into two categories:

1. Lot-to-lot variation of chemical composition.
2. Measurement errors such as those due to meter sensitivity, calibration standards, operation variations, temperature, and geometry effects.

Effect of Chemical Composition

One way of showing the effect of alloying elements on conductivity is to calculate the conductivity for the extremes for the composition range for the alloy. Table 1 shows the effects of the alloying elements on alloy 7075 resistivity.²¹ (Resistivity is used for calculations, since resistivity effects are additive.) In these calculations, an assumption is made as to the percentage of each element in solution. Using this information and the minimum, nominal, and maximum compositions for 7075, it is possible to calculate the resistivity of these compositions. When converted to conductivity, the significant effect of composition variation on an alloy's electrical conductivity can be seen. The composition limits of the registered range of the alloy 7075 could result in a conductivity variation of 4% IACS.²⁰

These theoretical calculations are supported by the example shown in Figure 8. Several lots of 7075 were quenched in warm or cold water and then checked for the W-temper electrical conductivity. Since magnesium has one of the larger effects on electrical conductivity, conductivity is plotted against magnesium content. Scatter bands for the data at both quench rates are shown. It is seen that for both quench rates the composition has a significant effect on conductivity. In fact, conductivities between 30.2 and 30.7% IACS (Fig. 8) can be achieved with two widely divergent quench rates due to the composition differences.²²

Measurement Errors

In an industry survey testing program sponsored by the Aluminum Association, 1" thick samples of 2024-T351 and 2124-T851, 7075-T651, and 7075-T7351 were supplied by each of three aluminum producers. A fourth producer supplied samples of 2024-T351 and 2124-T851. All fourteen samples were sent to 8 different locations to have conductivity measured. These locations were either fabricating plants or technical centers of various companies. The samples had a 1" circle marked on one surface and the conductivity was measured inside the circle. Each location used its own standards and procedures for their measurements. The conductivity was measured at a temperature between 68° and 80°F on all samples. A list of instruments used is given in Table 2.

Figures 9A through 9D show the distribution of conductivities measured on each sample. Several samples showed a range of measured conductivities of 1% IACS. The total distribution of conductivity readings for the four samples of each alloy is shown in Figures 10A through 10D as well as the specific data for each instrument. Some of the instruments show a range of conductivities for a sample that scarcely overlapped other instrument's measurements. This variation between instruments accounted for the largest portion of variation in the trial. Variations such as these were surprising considering the familiarity of the test locations with conductivity procedures. The fallacy of trying to measure conductivity to 0.1% and using those values for lot acceptance is pointed out by these large variations.

Figure 11 shows the differences between readings when operator, mode of operation (AC or DC) or source of calibration standards are varied. One observation for each of these conditions was chosen as an example from data supplied by the industry survey. Figure 11a shows the readings of one operator plotted as a base line with the measurements made by a second operator plotted as a deviation from the base line. All

other variables were held constant for this data plot. A similar situation is true for figures 11b and 11c. While there are some variations between readings when these variables are considered, the variations are smaller than the instrument-to-instrument variability.

Error is also introduced if a test standard is used at a different temperature from the metal being measured or if a test standard is used with a different temperature coefficient from the material being tested. Figure 12 shows the error introduced when various metal standards were used for calibration and readings taken on aluminum at various temperatures.²³

Geometry effects are shown in Figure 13 on readings taken near the edge of a piece of metal.²⁴ Depending on the type of eddy current instrument and its frequency, the depth and size of the region tested vary. Consequently, some instruments are more sensitive to measurements near an edge.

Conclusion

This paper has shown the value and the limitations of using electrical conductivity to assure the quality of aluminum plate. Electrical conductivity procedures are very useful as an in-process tool for monitoring quench variations over the surface of the plate. Conductivity is also a valuable tool for verifying that 7XXX series alloys in T7 type tempers are adequately aged to provide good corrosion resistance. However, it has been found that it is difficult to assure specific mechanical properties using electrical conductivity due to the many sources of variation. It is therefore concluded that the final decision on the acceptability of heat treated plate should depend on mechanical property testing.

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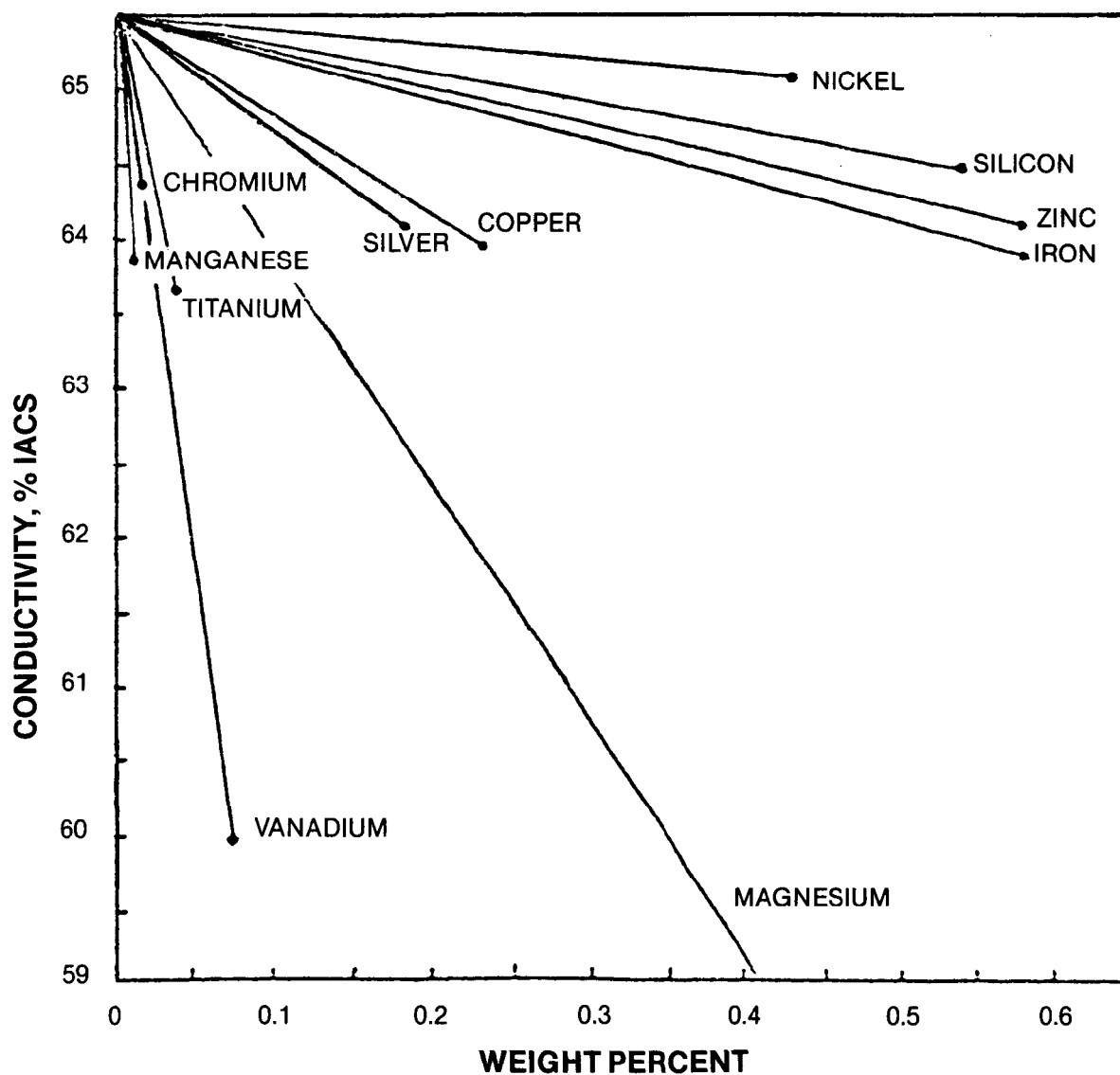


Figure 1 - Effect of alloying elements on the conductivity of aluminum.

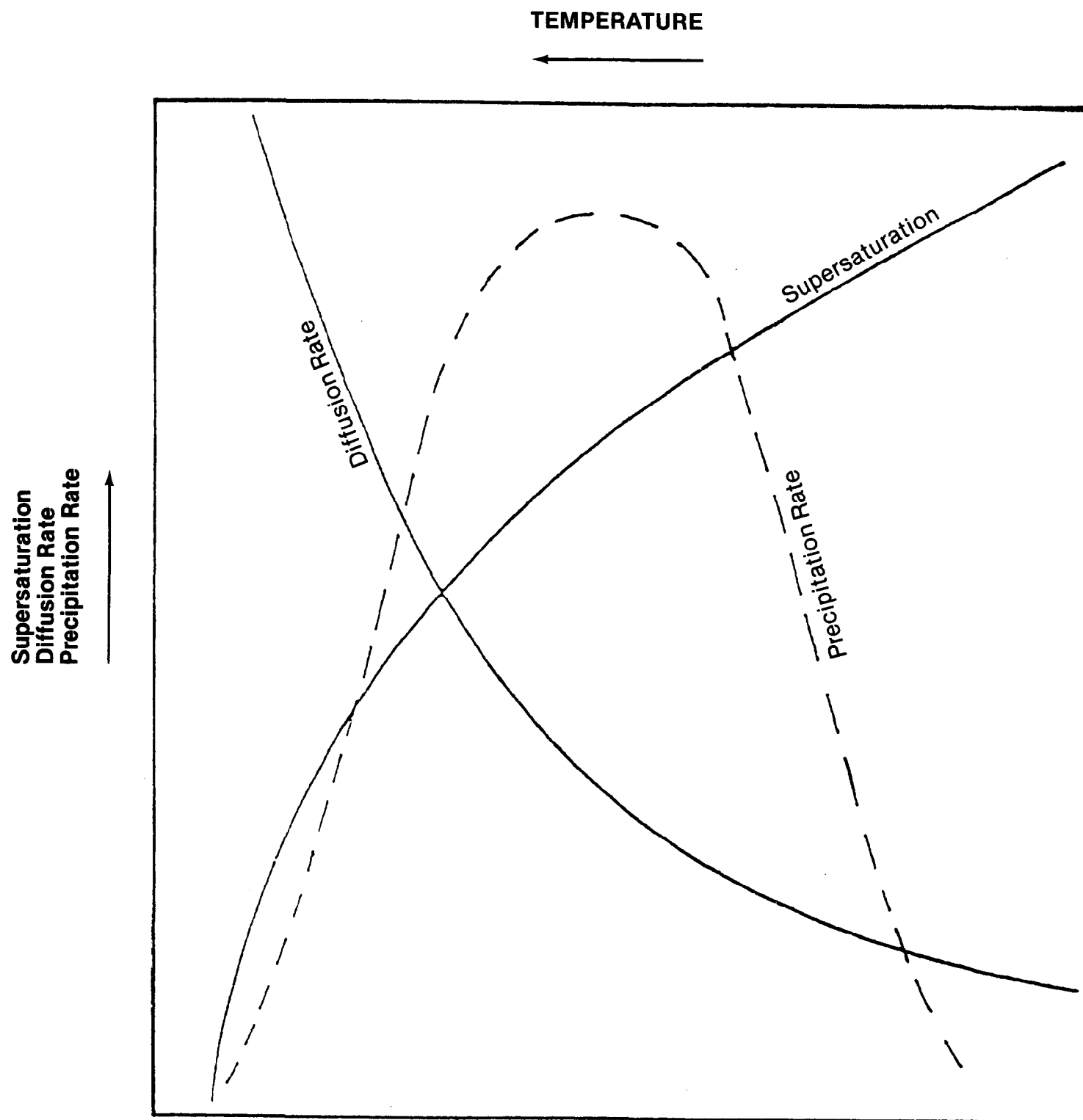


Figure 2 - This schematic illustrates how precipitation rate is dependent on both the supersaturation and the diffusion rate. The concept of a "critical temperature zone for quenching" is developed from this.