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# Interdiscipinary Project (ME/EE) for Students in Shop to Increase Conductivity of Aluminum Stock

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# A Review and Proposal for
# Increasing Conductivity of Aluminum Stock


## Abstract

While attempting to prototype a new electric machine design, University of Idaho researchers needed to manufacture a conductive yet nonmagnetic extrusion. Copper was originally selected for this extrusion but multiple difficulties arose in procuring this material, including cost. As a result, the researchers decided to investigate aluminum alloys, but the desired extrusion was not available in a suitable electrically conductive alloy. They then proposed but did not implement a test plan to determine if heat treatment of less desirable aluminum would be effective for increasing conductivity of the alloy to within a tolerable range. This paper reviews the relevant research and accepted standards for metals manufacturing and the measurement of conductivity in aluminum parts, and proposes a testing procedure for the purpose of determining whether aluminum conductivity can be adequately increased through heat treatment. If conductivity in 6061 T6 aluminum can be increased by more than 25% through the over aging of the metal, then 6061 aluminum will be useful as an alternative conductor in applications requiring non-standard extrusions of aluminum as conductive medium. The implementation of this test plan by an undergraduate/graduate student team presents a novel educational opportunity in which students can obtain hands on experience with eddy current meters and probes, nondestructive evaluation of materials, and the development of a manufacturing procedure for a materials modification.


## Introduction

A novel type of electric machine being developed at the University of Idaho requires the use of a continuous annulus of high conductivity material bonded within a laminated core. Due to materials shortages caused by the COVID-19 pandemic in addition to supply chain snags because of the offshore sourcing and development of materials such as copper and aluminum, it has become expensive to create this annulus from copper. When considering aluminum, however, it has also become impossible to purchase a piece of aluminum of the desired extruded profile from an electrically conductive alloy. From sources [1] and [2] it is evident that this problem has been growing for many years and extends to manufacturers within and without the United States, who are often forced to utilize less conductive alloys of aluminum for their electrical components if the specifications do not conform to standard profiles. It is therefore clear that a method must be devised to increase the conductivity of a premade extrusion of a less desirable alloy for electrical applications, and better document the required process. The documentation and development of this process provides a novel and worthwhile educational opportunity for a research team to explore modification of materials and nondestructive evaluation, a field which is projected to grow by 8.86% to 1795.8 million by 2028 [8]. In addition, researchers would gain invaluable experience developing a repeatable manufacturing process for the modification of conductivity in aluminum alloys.

## Background

It is an industry standard to test conductivity to determine metallic composition and alloying temper in various metals [5,6,7]. Such standards have been utilized for many years, and the use of eddy currents is common to test quality or degree of damage in various components both new and in-service. As this investigation is not meant to be an exploration of applications of eddy current testing beyond conductivity, this paper will not discuss more than that. For more information on eddy current techniques for other applications see references [5] and [6]. As conductivity and relative hardness testing has been performed for many years, there is a great deal of reliable data relating temper to conductivity. From a review of this data it is evident that it is possible to adjust the conductivity of an aluminum alloy within a narrow margin (25%) [1,5,6,7] by heat-treating the metal. Aluminum 6061 and 2219 were tested by sources [1] and [2] respectively and it was found that the conductivity of the material could be increased through long term heat treatment. Their process, however, was poorly documented and their results were questionable. Sources [10,11,12,13,14] discuss the use of Severe Plastic Deformation (SPT) methods such as High Pressure Torsion (HPT), Equal-Channel Angular Pressing (ECAP), and Accumulative Roll Bonding (ARB) in addition to others, which are proven methods to generate ultrafine grained and nanostructured materials that exhibit both high strength and high conductivity after further artificial aging. These methods, however, require use of advanced techniques and processing methods during manufacturing of the aluminum parts. As this paper discusses the modification of conductivity in premade, off the shelf extrusions, utilizing materials commonly available at many universities, a discussion of SPT methods will not be included in this paper. As SPT methods have been proven to produce parts with both high conductivity and high strength, it is an important method to study if a University or end user has such a capability. For further reading on these methods refer to sources [10, 11, 12, 13, 14] To utilize heat treatment to adjust conductivity in off the shelf aluminum it is, therefore, important to develop a procedure and create a data set which is experimentally gained and readily repeatable utilizing more commonly available materials.

## Review of Relevant Recent Work

Source [2] investigated the peak aging time for 2219 aluminum bar aged to a T6 temper to create the strongest bar possible given the alloy in question. In addition to their analysis of structural properties, they investigated the correlation between strength of the 2219 aluminum and the conductivity at each measured interval. Source [2] used a NorTEC 500D (Olympus Made) conductivity tester to measure the conductivity of the bars prior to testing their strength in a hydraulic press. They also highlighted that Guapariche et al. in their paper "Correlation of Strength with hardness and electrical conductivity for aluminum alloy 7010" [9] found a nonlinear correlation between strength hardness and electrical conductivity. Prabhu followed the following steps for their heat treatment of the 2219 alloy [2]:

Step 1: Solution Treatment at 535±5°C soaking for between 1 and 3 hours depending on bar diameter, with the 25 mm bars soaking for 1 hour, and the 120mm bars soaking for 3 hours. The 50mm bars and 75 mm bars soaked for 1.5, and 2 hours, respectively.

Step 2: Quenching in hot water maintained at 60-71 °C with a quench delay time of between 3 and 5 seconds. (*Note: the paper does not specify whether the quench was done in a tank, by water spray, etc. It can be implied that it was done in a tank, however details such as drop height into the tank, how the specimens were placed in the tank, agitation of the tank, time to quench, etc. is missing from the paper and therefore it is unknown what turbulence characteristics, quench delay times, and other factors may have impacted the resulting alloy and thus the results*).

Step 3: Aging at 191±5°C for eight different aging times from 20-29 hours.

Step 4: Air cooling to room temperature. (*note, steps 3 and 4 were combined in the paper*)

Prabhu found that the conductivity of the aluminum maintained a constant value for between 18 and 23 hours before increasing steadily over the course of the next 6 hours of aging time. They did note that for the 120mm bar the conductivity appeared to dip at 25 hrs. before increasing again but not to the original baseline. Therefore, conductivity of a piece with a larger cross section may decrease with heat treatment.   A dynamically non-uniform temperature profile with heat treatment introduces a spatially varying delay in the process. Introducing a large sample into a tank for quenching excites turbulence, directly impacting strength properties and uniformity of treatment. This may create pockets of non-uniform alloy material, introduce unwanted crystallization, and generate oxides on the surface. This decrease overall conductivity, and renders the result unacceptable. More information is, therefore, needed regarding the quenching of the material after the anneal [3]. In addition, the microstructure photographs included in the paper would suggest the development of some oxides and unalloyed pockets which may have rendered the conductivity results suspect. In addition, it also suggests that the specimens were dropped from a height into their respective tanks thereby generating turbulence which would effectively generate oxides within the material and modify grain structure [3]. This may imply that the conductivity increase measured by Prabhu should be higher, something that will need to be evaluated. The paper by Prabhu was of note as it included not only detailed steps and the type of equipment used for measurement, but included both detailed graphs and photographs showing grain structure which were informative about both the conclusions drawn as well as the conclusions that could be drawn from the work. This work provides a baseline for a methodology to develop a testing plan [2].

Similarly, and more importantly, Source [1], “The Effect of Aging on Microstructure, Mechanical Properties, and electrical conductivity of 6061 Aluminum Alloy for Circuit Breaker”, by Fellicia, Rochiem, et al, covers testing done on 6061 aluminum alloy and the effect of aging on the resistivity. This paper was of note as it investigated the effects of aging on 6061 alloy, which is the alloy of aluminum most easily available for purchase in an annulus or bar of the proper size for the electric machine application. Their literature review showed that the higher the aging temperature, the better the precipitation dissolvement is in alloys. They also determined that water will have the highest cooling speed of available cooling media. Their paper utilized a manufactured alloy of 6061 which showed a composition of 1.2%Mg, 0.6% Si, 98.2% Al, when according to the metals handbook [4], a 6061 alloy should be 1.0% Mg, 0.6% Si, 0.25% Cu, 0.25% Cr. The 6061-alloy provided by OnlineMetals, the desired source for the aluminum test specimens, is 98% Al, 0.04-0.35% Cr, 0.15-0.4% Cu, 0.7% max Fe, 0.8-1.2% Mg, 0.15% max Mn, 0.4-0.8% Si, 0.15% max Ti, 0.25% max Zn. The manufactured alloy for the purpose of the work is not an exact equivalent of the alloy recommended in the Metals Handbook or provided by OnlineMetals. Fellicia et. al. [1] aged their samples at 536 °C for one hour in a muffle furnace, they were cooled rapidly in water and returned to the muffle furnace where they were slowly heated to 160°C and held for 18 hours. The paper does not note how the temperature of the samples was measured, nor whether they had a single thermocouple in the oven or several thermocouples measuring the temperature of the samples, a problem also present in the paper by Prabhu [2]. The samples were then quenched and cooled to room temperature. Nothing in the paper indicates regarding quenching temperatures or quenching method which can have a marked effect on the growth of precipitates as well as the grain structure of the part, all of which will have an impact on the resulting grain structure and conductivity of the final product. This paper found that the result of artificial aging of the aluminum showed a conductivity increase by a multiple of 2.66. This value appears to be too high compared to the paper above, however, it does show that artificial aging may increase conductivity or conversely decrease resistivity, something that has been well documented in other media.

## Nondestructive Evaluation

From a review of nondestructive evaluation of materials by the Ohio State University Center for Nondestructive Evaluation of Materials [5], and "Non-Destructive Techniques Based on Eddy Current Testing" by Garcia-Martin, Gomez-Gil, and Vazquez-Sanchez [6], it is evident that as a method for testing conductivity, eddy current meters are a reliable and accepted evaluation technique. In eddy current testing of conductivity, conductivity is often computed in a value of %IACS which refers to a percentage of the **I**nternational **A**nnealed **C**opper **S**tandard (IACS) conductivity as established in 1914 by the United States Department of Commerce. The standard measures conductivity of materials as a percentage of the copper standard which is given to be 5.8001 x $10^7$ S/m at 100%IACS. This was measured in 1913. Many modern alloys of copper will be greater than 100%IACS and so their %IACS must be determined accurately through modern documentation and testing [5].

## Determination of Material Properties

Determination of material properties and temper as related to conductivity is held in the SAE International Specification AMS2658 Hardness and Conductivity Inspection of Wrought Aluminum Alloy Parts. Correlation of conductivity and temper in aluminum is well documented, supported by test results, and managed via standards.  This investigation seeks to amplify the standard to enhance the conductivity, not the hardness, of aluminum parts, enabling users to better understand and apply it. When aluminum is put through an annealing, solution treatment, and natural aging process to adjust temper, it tends to follow a cyclical pattern shown in Figure 1:

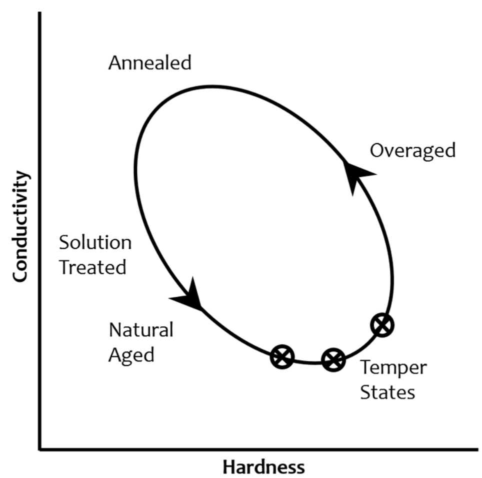


*Figure 1: Loop showing theoretical variation of conductivity with heat treatment adapted from [7]*

When the aluminum reaches an annealed condition, its conductivity reaches the highest level. As the aluminum goes through the solution's treated and natural aged states to reach each temper, the conductivity goes down and its hardness increases. Its conductivity increases again and the hardness decreases as the metal achieves an overaged condition. As the goal of this process is not to achieve a standard temper, but to adjust the conductivity of a non-ideal alloy of aluminum for the purpose of an electrical application, it is desirable to overage the aluminum so that the conductivity goes up. As this is done, conductivity trades off with hardness. Therefore, overaged parts, having enhanced conductivity but degraded hardness, should be eschewed for a structural application. Another chart, Figure 2, shows the temper states during heat treatment of 2024 aluminum adapted from the NDE website [5].

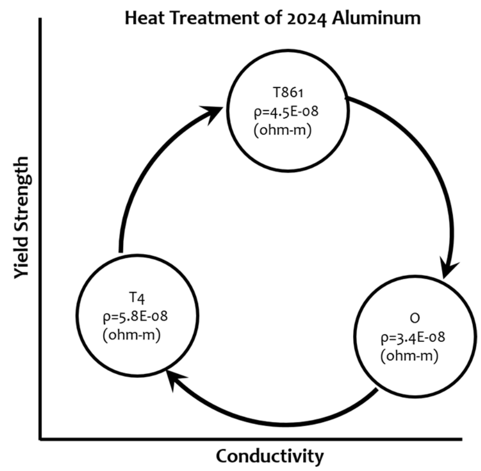


*Figure 2: Heat treatment cycle as given by NDE website [5] with resistivities for each temper added from [4]*

This chart displays the significant differences in the conductivities, (reciprocal resistivity shown), of various tempers of 2024 aluminum as the condition changes from an O temper to a T4 to a T861. This chart shows that the conductivity can be increased 25% between a T861 and O, and can be increased 41% between a T4 and an O. It is evident from an examination of the conductivities of the various tempers of 6061 from [4] that the conductivity of 6061 cannot be adjusted by such a wide margin, however it can be adjusted enough to make a difference for the desired application.

## Adjusting Temper in Aluminum

To properly adjust the temper in each aluminum alloy it is necessary to follow several steps:

1. Solution Treatment
2. Quenching
3. Forming and Straightening/Refrigeration
4. Precipitation Heat Treatment
5. Annealing

Solution treating typically produces a supersaturated solid solution through the sufficient application of heat. The part is heat soaked at a high enough temperature to achieve a nearly homogeneous solid solution and then quenched fast enough to maintain the solid solution. The lower limit of the applied heat should be above the temperature at which the metal becomes a complete solution to avoid exceeding the eutectic melting temperature; a condition that will result in a brittle metal. This condition cannot be detected without destroying the part. For 6061 aluminum from table 1 given in source [3] the solution treatment temperature is between 975 °F and 995 °F, (524 °C - 535 °C). Source [1] used the upper limit on the solution treatment temperature for 6061 aluminum. There is a normal thermal lag between the furnace and the part, and it will take time to equalize in temperature all the way throughout. Therefore, it is necessary to monitor parts within the furnace with more than one thermocouple measuring both oven and part temperature. These thermocouples should be attached to or buried in parts to obtain a good representation of hot and cold zones and the temperatures within them.

Quenching is done, either in a water tank or by a sprayer, to cool a part rapidly enough to avoid detrimental precipitation of solutes within the part and to produce a supersaturated solution at room temperature. It is important that the rate at which a part is quenched is controlled by both water temperature and movement This is because the cooling rate of the part through the 750 to 500 °F range can affect the end corrosion resistance. From the Tables given in [3] the maximum quenching temperature for 6061 aluminum is 100 °F. It is also important to note that the maximum delay in the time between the furnace and the quenching medium is 10 seconds.

Immediately after quenching, parts are soft enough to form and straighten, so it is during this stage that a part will be formed and straightened before the final precipitation hardening and anneal. Sometimes refrigeration is required to retard the process of precipitation so that straightening can be done to the part. Depending on the alloy, precipitation hardening at given time-temperature cycles is performed to stabilize the alloy. Some alloys precipitate at room temperature and thus do not require specific time-temperature cycles to precipitate adequately. Precipitation heat treatment is typically done at 240-375 °F for between 5 and 48 hours to achieve the desired ductility and tensile strength. From the Figure 11 of source [3] it is evident that the greatest strength increase is achieved for 6061 alloy at 250 °F, however the tensile strength can be decreased (and consequently the conductivity can be increased) by heat treating at 500 °F for between 1 and 10 hours.

The steps mentioned above are typically done at the foundry to achieve the desired temper for the end user, they are discussed here as the information regarding the behavior of aluminum during each step is important to the consideration of the anneal. After the end user receives the part they may reheat or anneal the part after performing their own working of the aluminum. The annealing process can either be a “stress relief anneal” or “full anneal.” A “stress relief anneal” is typically achieved by bringing a part to 650 °F and cooling to room temperature without any holding time, though it is typical to keep the part in the furnace for at least 1 hour to ensure that the part reaches equilibrium. When it is necessary to remove the hardening effects of a heat treatment, then a “full anneal” may be necessary and the part will be heated to between 775 and 825 °F and then slow cooled to 500 °F (50 °F per hour max cooling time) to permit max precipitate coalescence and therefore generate a part that has minimum hardness. It is the second, “full anneal,” that is desired in this case as a coarse and widely spaced precipitate should give a lower temper and thus higher conductivity per the material already discussed.

### Barrier to Proposed Work

The barrier to performing this work, however, came in the form of expense. The University of Idaho does not possess an eddy current conductivity tester, nor do they have the required probe. It was therefore necessary to procure one either through purchase, loan, or rental. To purchase an eddy current tester was not cost-effective and was superfluous as the university has no need to do eddy current testing except for this project. No loaner was found for the project. A rental for the project was quoted at $1200.00/month; this added expense rendered the use of aluminum significantly more expensive than using the copper annulus which led to the decision not to proceed with this testing. Despite that decision, the research team decided that it would be worthwhile to publish on the proposed test plan as the work still has merit for future projects requiring difficult-to-obtain extrusion profiles in electrical aluminum. In addition, a third party who may have the necessary equipment and may be willing to perform the work in this paper can simply follow the steps for testing laid out herein.

## Proposed Work

The proposed test would involve cutting 6061 T6 temper 1.5" thin wall aluminum tube into 2-inch sections. Each aluminum tube should be purchased in one foot long bars and each bar should be labeled with a letter, A-Z, denoting the bar that it was cut from and a number, 1-6, denoting sample # cut from the aluminum so that samples are labeled in the following manner, A-1, A-2, B-1, B-2, etc. All samples should be labeled through stamping or etching so that the label is not lost during heat treatment. Once all samples are cut to size, utilize a conductivity tester to test and record the conductivity of each sample. Each sample should be measured at least four times to average out any errors, and all outliers should be thrown out and measurements re-taken to ensure the validity of measurements. Initial measurements should be compared with the %IACS conductivity reported by OnlineMetals to verify that the measurements are as expected. The conductivity tester should be an eddy current conductivity meter with a maximum measurement tolerance of ±0.5% IACS, with a higher sensitivity and lower measurement tolerance being more desirable. The use of a surface probe should be sufficient; however, an insertion probe may give better results.

Once all samples have been tested and the conductivities recorded, then one sample from each bar should be set aside as a control and the rest of the samples will be set aside for heat treatment. On each tray, all samples should be mixed so that samples from each bar are exposed to similar conditions. This should ensure that all variations in grain structure between the bars are accounted for, and any variations in oven temperature are averaged out over the number of samples. All bars should be accounted for on all trays, in other words each tray should have samples from each of the letter-labeled aluminum tubes used, and should not have all of one letter present on a tray. This should ensure that any variations in the manufacture of the aluminum or the temperature within the oven are averaged out by ensuring that samples of all bars are exposed to all variations present within the furnace. On each tray thermocouples should be affixed to the inside and outside of the bottom corner, top corner, and center of the tray and temperatures should be measured during the entirety of heat treatment. Temperature between the thermocouples should not vary by more than 3 degrees. Variance of more than 3 degrees indicates the presence of significant cold and hot spots in the furnace and may require service. Once all trays are set up the furnace should be pre-heated to 800 °F or 425 °C. Trays should then be placed within the furnace, and the furnace should be allowed to return to temperature. When the furnace and all thermocouples read the same temperature to within three degrees, the timer should be started and all parts should be soaked for two hours. At the end of two hours the oven should be decreased in temperature by 100 °F and the thermocouples should be monitored to make sure that the samples do not decrease more than 50 °F in one hour. At the end of an hour the temperature should be decreased again and thermocouples should be monitored. This should be repeated until the samples reach room temperature. Once the samples reach room temperature, all samples should be tested for conductivity. Conductivity testing should be repeated every 12 hours for one week and the results should be noted. As previously, multiple readings should be taken and any outliers should be discarded. At the end of testing conductivity should be plotted and results should be analyzed to determine how much conductivity changes over the course of natural aging.

## Goals of Testing

The goals of the testing are:

1. Determine whether an anneal can significantly decrease the conductivity of aluminum.
2. Determine how much resistivity decreases (conductivity increases) after heat soak at 2 hours in 800 °F or 425 °C.
3. Determine how much resistivity increases over duration of natural aging and develop a curve fit that can be used to estimate resistivity at a given time after initial anneal.
4. Determine next steps, and whether additional tests will be required.

## Pass Criteria

For aluminum post-production anneal to be effective to make 6061 T6 aluminum of value for use as a conductive medium in prototype electric motors and other prototype electric components, the resistivity must decrease by at least 20%. The conductivity should not decrease by more than 0.5% IACS per week during natural aging, or the conductivity of the aluminum can become problematic for electrical applications that rely on accurate resistance measurements such as electric machine rotors, contacts, breakers, etc. If the resistance of the part increases by too much, and a lower resistance is expected, it could cause problems for development of new controls, testing, or utilization in any given circuit. It can also be difficult to isolate and measure resistance of individual metals within a circuit, therefore computation of resistance from part geometry will sometimes be utilized. If the resistivity of the part varies from the recorded resistivity, resistance calculations will be invalid.

## Educational Value of the Work

The behavior of materials is one of the cornerstones of a solid understanding of how energy transfers through various systems. From the transmission of heat through a heat exchanger to the conduction of electricity in a carbon fiber conductor, the transmissibility of energy through materials is an important topic to understand. It is well known in the teaching of languages that rote memorization and drills can only do so much; scholars learn much better and faster by applying the language that they are attempting to learn in a real scenario. As in languages and many other disciplines, this is also true in engineering. If an understanding of the behavior of materials is critical to a scholar's whole understanding of the physical world, necessary to develop better systems and further innovate within their fields, then it is important that scholars can learn that information through real application. It is for this reason that the development and testing of this process by a graduate and undergraduate team of students would be of value in an educational setting. By applying first principles, the scientific method, critical thinking, and problem-solving skills to this process, students will learn to analyze and evaluate previous work as a starting point to create new processes and for them to grow their understanding of materials. In addition, students will learn invaluable skills in nondestructive evaluation of materials, a field which is critical to ensuring that components and parts are free of defects which can render them incapable of performing the function for which they were designed. Students will also gain insight and understanding in how the annealing process can be applied to modify existing materials for different uses, a skill which helps them in learning flexibility within their projects as they have learned how to modify what is available to better fit their end use.

## Conclusions

The University of Idaho did not have the opportunity or resources to perform this investigation, though it is a worthwhile investigation to develop a procedure through which aluminum extrusions in higher resistivity aluminum alloys can be altered for use in electrical applications. Conductivity is often used to determine the degree of heat treatment and strength of a given nonferrous metallic part. It is, therefore, well known and documented that conductivity can change with the degree of heat treatment. Most of this testing has been done with a focus on the strength characteristics of the aluminum after heat treatment, with only minor focus on the ideal procedure to change the aluminum conductivity. Therefore, it is necessary to perform testing with a focus on the change in conductivity as opposed to the change in structural properties. In addition, greater understanding of the change in conductivity with various heat treatment methods can help engineering and science students better understand the relationship between grain structure and conductivity, which can assist in the development of better conductive materials through the generation of artificial conductive lattices with desired conductivity profiles without being superconductive.

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