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Aluminum/calcium deformation metal-metal composites after conversion to Al2Ca intermetallic reinforcement

Charles Czahor

Iowa State University

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Aluminum/calcium deformation metal-metal composites after conversion to Al$_2$Ca intermetallic reinforcement

by

Charles Frederick Czahor

A thesis submitted to the graduate faculty
in partial fulfillment of the requirements for the degree of
MASTER OF SCIENCE

Major: Materials Science and Engineering

Program of Study Committee:
Iver E. Anderson, Major Professor
   Alan M. Russell
   James D. McCalley

The student author, whose presentation of the scholarship herein was approved by the program of study committee, is solely responsible for the content of this thesis. The Graduate College will ensure this thesis is globally accessible and will not permit alterations after a degree is conferred.

Iowa State University

Ames, Iowa

2017

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ABSTRACT

Deformation-processed metal-metal composites (DMMCs) provide an appealing approach for producing lightweight materials with high strength and high conductivity. DMMCs can be produced by powder metallurgy and severe plastic deformation resulting in nano-filamentary reinforcement. Al/Ca composites with monolithic construction have shown promise as next-generation overhead transmission conductors. Previous research has shown that these materials tend to form various intermetallic species when exposed to elevated temperatures resulting in the degradation of properties. This study examines the effect of using a reduced loading of Ca and intentionally converting the reinforcement to an intermetallic species to produce a material with enhanced high-temperature stability while retaining superior performance properties. Al/Ca (11.5 vol.%) composites were produced and converted to Al/Al$_2$Ca (18 vol.%) by heat-treatment at 260°C. In addition to the effect of reinforcement material, the influence of filament spacing was studied. The transformation to Al$_2$Ca was analyzed by differential-scanning calorimetry and scanning electron microscopy. Tensile strength and electrical conductivity were investigated for unconverted and converted materials as well as samples that had undergone extended heat treatment. The measured material properties were used in line sizing calculations to determine the benefits of using these composites for high-voltage direct-current transmission.
CHAPTER 1. INTRODUCTION

A 48% increase in worldwide energy demand is expected by 2040, which will require expansion of electrical power transmission infrastructure [1, 2]. Expanded long-distance transmission grids in China, the United States, and elsewhere are expected to make greater use of high-voltage direct current (HVDC) transmission, the preferred technology for long distances [3]. Conventional aluminum-conductor steel-reinforced (ACSR) conductors are not well suited for HVDC transmission due to the presence of the heavy, poorly conducting steel core needed for strength and sag-resistance. Al/Ca composite conductors with monolithic construction produced by powder metallurgy and deformation processing have shown promise as a possible next-generation conductor for this application.

Deformation-processed metal-metal composites (DMMCs) provide an appealing approach for producing lightweight materials with high strength and high conductivity. DMMCs can be produced by powder metallurgy and severe plastic deformation resulting in nano-filamentary reinforcement. Extensive study of this class of materials has shown that they exhibit strength that increases exponentially with true strain while maintaining conductivity close to the rule-of-mixtures prediction [4]. Both materials in the composite must be highly ductile in order to withstand the extensive deformation processing without fracturing. The proposed conductor material utilizes Al as the primary phase and Ca as the secondary reinforcement phase, both starting as elemental powders. They are blended and deformed into sub-micron-thickness filaments with extremely high aspect ratio during wire drawing, resulting in interface strengthening. Al and Ca are ductile fcc metals with high conductivities, similar mechanical properties, and low densities.
The first-generation of Al/Ca conductors proved the strengthening mechanism of the material but was limited by the coarse Ca powder size used [5]. The second-generation material, Al/Ca (20 vol. %), was made with high-purity powders with smaller powder particle sizes, enabling strengths superior to existing conductor technologies [6]. One key finding from these studies was the identification of a transformation of the reinforcing Ca phase to Al$_2$Ca intermetallic at temperatures as low as 175˚C, a temperature sometimes reached by transmission conductors during periods of heavy electrical demand [5, 6].

This study examines the effect of intentionally converting the reinforcement phase to an intermetallic species to produce a material with high-temperature stability while retaining the superior performance properties that have been shown in the prior generation materials. A reduced initial volume loading of Ca was necessary to compensate for volume expansion during transformation and an expected increase in resistivity. A formulation with 11.5 vol.% Ca was chosen with the aim of producing a composite with 18 vol.% Al$_2$Ca, found in previous research to be a desirable DMMC reinforcement fraction [7]. Microstructure, temperature stability, conductivity, and mechanical properties were investigated in both Al/Ca and Al/Al$_2$Ca composite samples. The design criteria and performance of these materials as overhead conductors were also studied.
CHAPTER 2. BACKGROUND INFORMATION

This chapter will provide relevant background information that has motivated the research that will be presented. A brief history of previous studies of DMMCs will be given in addition to an overview of Al/Ca research progress to date. Additionally, the options for overhead power transmission will be discussed along with some of the existing conductor technologies available.

2.1 Early DMMC research

Composite materials consist of two or more different phases in order to achieve a combination of properties that cannot be attained from either phase by itself. The primary phase is referred to as the matrix, which surrounds the second dispersed phase. The matrix can be a metal, ceramic, or polymer with three different possible reinforcement types including particle, fiber, or structural. [8]. Deformation metal-metal composites consist of ductile metals as both the matrix and dispersed phase with fiber reinforcement being created by mechanical working. DMMCs can be prepared by either powder metallurgy or co-melting two metals that are miscible as liquids but immiscible as solids then deformation by extrusion, swaging, and drawing to produce wire or rolling to make sheet. The final microstructure is typically sub-micron thick phases due to the large amount of deformation imparted on the material [7].

Typically, metal matrix composites exhibit strengths that are linearly dependent on the volume fraction of the reinforcement phase. The earliest Cu-Nb DMMCs produced by Bevk et al. showed that extensive deformation of reinforcements could lead to an exponential increase in strength that greatly exceeded rule of mixture predictions. These materials also displayed good retention of electrical and thermal conductivity when using 18 to 20 vol.% Nb reinforcement [4].
The ability to achieve both high strength and high conductivity simultaneously is the main appeal of using this type of material.

Most studied DMMCs use a face-centered cubic (fcc) matrix (Al, Cu) with the earliest using body centered cubic (bcc) metals as the second phase. This combination results in a convoluted ribbon shaped morphology of the second phase embedded in the matrix [4, 9, 10]. In the early 1990’s, Ames Laboratory produced various DMMCs with Ti, Mg, Al, Sc, and Au as the matrix phase [7]. Much attention has been placed on Al matrix DMMCs with Nb, Ti, Mg, Sn, and Fe second phases being studied. These materials also showed exponential strengthening with high electrical conductivity [11, 12, 13, 14]. Despite the fact that all of these materials all exhibited good material properties, aluminum/calcium DMMCs have been developed specifically for the intended application of overhead power transmission.

2.2 Previous Al/Ca research progress

Aluminum is almost universally accepted as the best material for overhead conductors because of its high conductivity and low density. The selection of calcium as the reinforcement phase for DMMC conductors was based on the combination of high conductivity, low cost, and extremely low density. In addition, aluminum and calcium have similar strengths and are highly ductile enabling them to withstand the extensive deformation required to achieve sub-micron filaments. A more detailed discussion of the selection of the combination of Al and Ca is provided by [15] and [6].

Study of the first generation of Al/Ca (9 vol.%) composite showed the strengthening effect typical of DMMCs, but was limited by the large size (1.2 mm) of the Ca granules that did not allow
filaments to reach the sub-micron level [5]. Second generation Al/Ca (20 vol.%) composites exhibited an ultimate tensile strength (UTS) of 476 MPa, exceeding the strength of all current commercial stranded conductors. This was enabled by a smaller Ca powder size (<200 µm) and a relatively high reinforcement fraction [6]. Both of these formulations showed a ribbon shaped second phase despite the fact that a cylindrical filament morphology was expected for a fcc metal (Ca) in a fcc matrix (Al). This has been explained by a possible temporary phase transformation of Ca filaments from fcc to bcc during processing [15, 16].

The elevated temperature performance of Al/Ca (20 vol.%) composites was studied, and it was found that Al₄Ca intermetallics are formed at temperatures as low as 177°C. Two different exothermic events occur upon heating which correlate with the formation of Al₄Ca and Al₂Ca [6]. These two phases are delineated in the Al/Ca binary phase diagram shown by Figure 1 [17].

Figure 1. Al/Ca binary phase diagram.
Al$_2$Ca was found to be the more stable phase, and its formation resulted in a growth of the reinforcement filaments and an increase in electrical resistivity. In order to enhance the high-temperature stability of Al/Ca DMMCs, the initial volume fraction of Ca could be transformed to Al$_2$Ca after all deformation processing was completed.

2.3 Current overhead power transmission conductor technologies

As the makeup of global energy production shifts from predominantly fossil fuels to a complex blend of sources, more efficient long-distance power transmission will be necessary. High-voltage direct-current transmission (HVDC) becomes preferred to alternating-current (HVAC) technology when transmission line length exceeds a certain break-even distance as shown by Figure 2 [18].

![Figure 2. HVDC break-even distance.](image)
Intermittent sources such as wind and solar are typically located in remote areas far away from population centers and will likely make greater use of HVDC transmission in the future [19]. HVDC is often limited by the high cost of conversion equipment and difficulties in breaking elevated DC current [18]. HVDC does, however, offer several benefits compared to HVAC, including: greater power carrying capacity [18, 20], higher stability and reliability [18, 20, 21], freedom from compensation for inductance and reactive power [18], fewer conducting wires and towers [18, 22], and the absence of skin effects that result in localized surface heating [18]. The skin effect enables conductors with poorly conducting core materials such as conventional aluminum-conductor steel-reinforced (ACSR) to perform well for AC because current is concentrated in the outer (aluminum) portion of the conductor. ACSR as well as a selection of more recently developed overhead conductors are shown in Figure 3 and defined in Table 1 [23].

Figure 3. Selected overhead transmission conductor technologies.
Table 1. Commercial overhead transmission conductors.

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>ACSR</td>
<td>Aluminum Conductor Steel Reinforced</td>
</tr>
<tr>
<td>ACCC</td>
<td>Aluminum Conductor Composite Core-CTC Global&lt;sup&gt;1&lt;/sup&gt;</td>
</tr>
<tr>
<td>ACCR</td>
<td>Aluminum Conductor Composite Reinforced -3M&lt;sup&gt;2&lt;/sup&gt;</td>
</tr>
<tr>
<td>ACAR</td>
<td>Aluminum Conductor Alloy Reinforced</td>
</tr>
<tr>
<td>AAAC</td>
<td>All Aluminum Alloy Conductor</td>
</tr>
</tbody>
</table>

ACSR is the most widely used conductor because of its ability to combine an acceptable level of strength and conductivity at a low cost. For DC current flow, however, the steel core acts as a “dead zone”, and the conductivity is reduced. Another disadvantage of ACSR is the large mismatch between the thermal expansion coefficients for Al and steel, which can result in birdcaging and thermal fatigue [24]. Newer materials have sought to replace the steel core with lighter and stronger materials in order to increase the thermal limit of the conductor and the current carrying capacity. ACAR uses Al alloy in the core but is not strong enough for long spans [25, 26, 27]. ACCR was invented by 3M and uses a core with 50 vol.% aluminum oxide fibers in an Al matrix. ACCR has very good sag resistance but is limited in its use by high cost and mediocre DC conductivity [25, 26, 28]. ACCC, invented by CTC Global, has a polymer matrix carbon and glass fiber reinforced composite core. AAAC is a conductor that has a single material for the entire cross-section made with precipitation hardened aluminum, but it is limited in strength and sag resistance [25, 26].

The issue with ACSR and the other materials that seek to replace it is that they are not specifically designed for DC. Al/Ca conductors can achieve high strength and high conductivity simultaneously without the need for a steel core making them extremely lightweight.
CHAPTER 3. EXPERIMENTAL PROCEDURE

This chapter will cover both the production steps necessary for sample preparation as well as the techniques used to gather results. Previously produced Al/Ca (20 vol.%) samples were analyzed in addition to the newest formulation. The newly produced samples were the primary focus of this work.

3.1 Samples Preparation

An Al/Ca conductor sample was prepared starting from metal powders produced at Ames Laboratory. Al powder with 99.99% purity was produced by a gas atomization reaction synthesis (GARS) process with sizes 45-75 µm being used. Ca of 99.5% purity was made by centrifugal atomization with a rotating quench bath (CARQB), a system specifically designed for producing fine Ca powders. The first-generation material [5] used large commercial Ca granules (1.2mm), and the second [6] used Ames Lab Ca with D_{50}=200µm. A smaller starting Ca powder size allowed for filaments in this third-generation material to be smaller after deformation, so Ca of even smaller size (75-125 µm, D_{50}=111) was selected for the material used in this study. The formulation used to produce this sample included a reduced loading of calcium (11.5vol.%) with the remainder being aluminum (88.5vol.%). This reduction was made to allow for the volume expansion of Ca to intermetallic species resulting in a reinforcement fraction that was desirable based on previous findings as shown by Figure 4 [7].
Figure 4. Reinforcement fraction after complete conversion to intermetallic species.

Powders were weighed (155.45 g Al, 11.45 g Ca) in an inert atmosphere glovebox then blended with a Turbula multi-axis mixer for 30 minutes. The mixed powders were die compacted with a pressure of 61.2 MPa into cylindrical green bodies (diameter=72.1 mm) giving a compact density of 83.8% of the rule of mixtures (ROM) value. This value is in close agreement with the expected compressibility of Al powder as shown by Figure 5 [29]. The slightly higher density can likely be explained by the fact that relatively small powder sizes were used.

Figure 5. Compressibility of atomized aluminum powder as a function of pressure [29].
The compacted powder “pucks” were stacked in a pure Al (1100-H14 alloy) can with outer diameter 90.7 mm, inside diameter 78 mm and interior height 196.8 mm. The can was wrapped in heating tape to warm it to about 200°C as it outgassed under vacuum ($10^{-6}$ Torr) to remove moisture adsorbed on the powder particles, and then it was sealed by electron-beam welding (Figure 6).

![Figure 6. Extrusion can loaded with Al/Ca compacts sealed by E-beam welding.](image)

**3.2 Deformation Processing**

Indirect extrusion was performed at the TU Berlin Extrusion Research and Development Center with an exit die diameter of 21 mm, giving an effective extrusion ratio of 14.9 when accounting for the porosity and void space present in the billet. The billet was preheated to 285°C, and the die exit temperature was monitored in addition to other processing conditions. This temperature was high enough for dynamic recovery of both Al and Ca (0.4 $T_m$) but low enough to avoid the formation of Al/Ca intermetallic compounds in that time frame that could initiate cracks.
during extrusion. The deformation true strain can be calculated according to Equation 1 where \(d_i\) and \(d_f\) are the initial and final wire diameters, respectively.

\[
\eta = \ln \frac{A_i}{A_f} = 2 \ln \frac{d_i}{d_f}
\] (1)

In order to account for the porosity in the billet and the space between the compacts and the can (Figure 7), a correction was made to determine the effective starting diameter.

![Figure 7. Void space in extrusion can.](image)

Equation 2 shows how the deformation true strain is dependent on the different areas of the starting piece and the final extruded rod.

\[
\eta = \ln \left( \frac{A_{can} + A_{puck}}{A_{final}} \right)
\] (2)

where,

\[
A_{can} = \frac{\pi}{4} [OD_{can}^2 - ID_{can}^2]
\] (3)
\[
A_{\text{puck}} = \frac{\pi}{4} \left[ (OD_{\text{puck}}^2)(1 - \text{porosity}) \right]
\]  

(4)

By combining these three expressions, a true strain of 2.7 after extrusion was calculated by Equation 5. Given the size of the extrudate, this strain corresponds to an effective starting diameter of 81.1 mm.

\[
\eta = \left( \frac{[OD_{\text{can}}^2 - ID_{\text{can}}^2]}{OD_{\text{final}}^2} + \left[ (OD_{\text{puck}}^2)(1 - \text{porosity}) \right] \right)
\]

(5)

A rod with a length of approximately 275 cm was returned to Ames Lab to undergo further deformation processing. Ultrasonic inspection of the tail section was utilized to identify the point at which there was no longer material from the extrusion can in the core of the rod. After removing this portion, the rod was sectioned into quarters, and the can material was machined from the rod’s exterior with a lathe. The final rod diameter after removal of the pure Al outer sleeve was 15.8 mm, which was used to adjust the effective starting diameter to 62.9 mm to account for the reduction in size by the lathe, which produced no additional plastic deformation of the Al/Ca portion of the specimen.

The rod was reduced at room temperature by swaging through a series of dies to 0.690 mm. At this point wire drawing was used to further reduce the material to a final diameter of 0.11 mm. The excellent ductility of the components in the composite allowed all deformation processing to be performed without any stress-relief annealing. Various sample diameters were retained as deformation progressed to study the effect of strain on material properties. Table 2 shows the different wire diameters used for this study along with the corresponding true strain values.
Table 2. Wire sizes and strain levels for study of third generation Al/Ca wires.

<table>
<thead>
<tr>
<th>Diameter (mm)</th>
<th>( \eta )</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.97</td>
<td>6.11</td>
</tr>
<tr>
<td>2.16</td>
<td>6.74</td>
</tr>
<tr>
<td>0.94</td>
<td>8.41</td>
</tr>
<tr>
<td>0.50</td>
<td>9.67</td>
</tr>
<tr>
<td>0.40</td>
<td>10.1</td>
</tr>
<tr>
<td>0.31</td>
<td>10.6</td>
</tr>
<tr>
<td>0.20</td>
<td>11.5</td>
</tr>
<tr>
<td>0.11</td>
<td>12.7</td>
</tr>
</tbody>
</table>

3.3 Conversion of Filaments

The main goal of this study was to examine the effects of intentionally exposing Al/Ca DMMCs to elevated temperatures in order to observe how filaments were converted to intermetallic species and evaluate the performance of the resultant material. Both previous and current generation materials were studied in order to plan the appropriate method for processing these samples.

3.3.1 Differential Scanning Calorimetry

Differential Scanning Calorimetry (DSC) experiments were performed to study high-temperature events taking place in Al/Ca materials. A Netzsch STA449 F1 DSC system was used with heating rates ranging from 5-20°C/min for various samples of both Al/Ca (20vol.%) and Al/Ca (11.5 vol.%). Samples with various true strain values were examined to determine whether the heat treatment process required different exposure times for different size samples.
3.3.2 Conversion to Al/Al$_2$Ca

Using the results of DSC tests, it was determined that samples could be converted to Al$_2$Ca reinforcement with a short heat treatment. Short lengths of wire were sealed in Ar-filled quartz ampoules and heat-treated in a temperature-controlled tube furnace at 260°C for various times depending on size as shown in Table 3.

<table>
<thead>
<tr>
<th>Diameter (mm)</th>
<th>Time at 260°C (min)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.1</td>
<td>2</td>
</tr>
<tr>
<td>0.2</td>
<td>3</td>
</tr>
<tr>
<td>0.3</td>
<td>5</td>
</tr>
<tr>
<td>0.4</td>
<td>6</td>
</tr>
<tr>
<td>0.5</td>
<td>8</td>
</tr>
<tr>
<td>1</td>
<td>10</td>
</tr>
<tr>
<td>2</td>
<td>12</td>
</tr>
<tr>
<td>3</td>
<td>15</td>
</tr>
</tbody>
</table>

Table 3. Heat treatment time for sample conversion.

DSC on these samples was run to confirm that the intermetallic transformation was complete. All further analysis was completed on both unconverted (Al/Ca) and converted (Al/Al$_2$Ca) samples at various levels of true strain.

3.4 Scanning Electron Microscopy

Microstructure was studied using a FEI Teneo LoVac Field–Emission Scanning Electron Microscope (FE-SEM). SEM images were taken before and after transformation to determine
whether the heat treatment process had gone beyond simple conversion to the intermetallic and caused undesirable sinusoidal instabilities in the reinforcement filaments [30, 16]. Samples were prepared for examination by dry polishing to avoid the corrosive effects of water on the calcium filaments. The smallest wire samples (η=12.7) utilized focused ion-beam cutting prior to imaging in lieu of polishing to avoid exposure to air and water.

3.5 Four Point Resistivity Measurement

The electrical conductivity of wires at all strain levels included in Table 2 for both Ca and intermetallic reinforced samples was determined by the four-point probe measurement technique according to ASTM B193-16 [31]. A series of currents was applied with a Keithley 6220 Precision Current Source, and the voltage difference was measured with a Keithley 2182A nanovoltmeter. The accuracy of this measurement technique was confirmed with copper and stainless-steel standards of known conductivity. Measurements were taken at room temperature (20°C), which allows direct comparison to tabulated values of other conductors [23]. Given that the instruments used were very precise, the largest source of error came from the dimensions of the material, especially for small samples. The sample size was determined by measurement with calipers, microscope imaging, and weighing of wires.

3.6 Tensile Testing

Tensile testing was done with multiple instruments to accommodate the various wire sizes that were examined. The larger samples (η<7) were tested using an Instron 3367 instrument with an elongation rate of 2 mm/min. For samples with 8< η<12 the tensile strength was determined using a Zwick/Roell Z 2.5 instrument with the same elongation rate. For the 0.11 mm diameter (η =12.7) wire, tests were completed at Psylotech’s facility using their μTS under microscope universal test
system allowing for precision measurements at low forces. For each technique, the average of at least three independent measurements of the ultimate tensile strength (UTS) was reported. UTS was used since it is more reproducible and reliable than yield strength for small specimens and is the strength value most often cited for transmission conductor materials [16].
CHAPTER 4. STRUCTURE-PROPERTY RELATIONSHIPS

In addition to the properties that will directly affect the performance of the material, several other characteristics have been investigated. Numerous considerations must be made in order to produce and operate with these materials. The results presented will help explain how the desired material properties are influenced by processing conditions and intelligent design.

4.1 Extrusion

The extrusion of the Al/Ca (11.5 vol.%) billet both closed the porosity remaining from compaction and reduced the diameter of the sample. Figure 8 shows that the force required steadily increased as the ram was displaced until approximately 30 mm. At this point the void space in the can collapsed and the extrusion process continued with fully dense material.

![Figure 8. Extrusion temperature and force profile for Al/Ca (11.5 vol.%).](image-url)
The temperature at the die outlet starts off at the preheat temperature of 285°C and rises as a result of frictional force [32]. Elevated temperature was used in order to reduce flow stress and allow for dynamic recovery [33]. The extrusion ratio of 14.9 that was used was significantly higher than the extrusion ratio (i.e., 11) used in previous samples. This increase was made based on previous findings indicating that a reserve of ram force capacity was available to permit higher forces to be applied [5].

After extrusion, it was decided that the material from the extrusion can should be removed from the rod since it was desired to study only the properties of Al/Ca composite, not of pure-Al-clad Al/Ca composite. Prior to the removal of the outer aluminum “shell”, ultrasonic inspection was used in order to determine the point where there was no longer can material in the center of the extrusion. Figure 9 shows multiple cross-sections of the rod with the presence of the can material in the center being evident.

Figure 9. Cross-sectional view of tail section of extruded rod.
The can material in the tail section of the extrusion is introduced into the core of the rod due to the way in which the material flows during the extrusion process. Figure 10 shows the four different types of flow patterns that are generally observed during extrusion [32].

![Figure 10. Schematic of the four different types of flow in extrusion.](image)

Based on the fact that indirect extrusion was used with aluminum being the primary material, it was assumed that flow pattern A was present according to the study of other aluminum extrusions [32, 33]. In this case the metal at the center of the billet moves faster than the metal at the periphery, leading to the presence of outer can material in the center of the rod near the end of the extrusion. Once the tail end of the rod and the outer shell had been removed, further deformation processing produced Al/Ca wires of various sizes that were used for the remainder of the study.

### 4.2 Differential scanning calorimetry measurements on Al/Ca (11.5 vol.% and Al/Ca (20 vol.% composite)

Differential scanning calorimetry tests were performed on Al/Ca (20 vol.%) composite wires with $\eta=9.95$ at different heating rates to identify microstructure transformations at elevated temperatures. Figure 11 shows that for experiments run with heating rates of 5, 10, 15, and 20
K/min there are two exothermic events taking place. Previously reported work confirmed these events to be the formation of Al₄Ca and Al₂Ca intermetallics by X-ray diffraction [5].

![DSC results for Al/Ca (20 vol.%) at various ramp rates.](image)

*Figure 11. DSC results for Al/Ca (20 vol.%) at various ramp rates.*

It can be seen that the use of a greater heating rate results in the peaks being shifted to higher temperatures. Using the results of these experiments, a time-temperature-transformation (TTT) diagram was constructed that shows how the formation of these two intermetallics takes place in succession and is dependent on heating rate (Figure 12).
The findings from experiments on Al/Ca (20 vol.%) were used to help design experiments for the current-generation material and to help gain a better understanding of the transformation process. In addition, the determination that Al₂Ca was the more stable compound guided the current formulation to allow for the use of an appropriate amount of reinforcement phase. Figure 12 showed that a temperature in excess of 250°C was needed to complete both transformation events for samples with 20 vol.% initial calcium loading.

The intent of this current study was to transform the reinforcement phase to Al₂Ca, so it was desired to identify the temperature of this particular event for the current formulation. Figure 13 shows the results of DSC experiments on three different wire samples that had not received any
heat treatment prior to testing with a heating rate of 20 K/min since it was shown to provide adequate peak resolution on Al/Ca (20 vol.%).

Figure 13. DSC curves of Al/Ca (11.5 vol.%) wires with various deformation true strain levels.

The Al$_2$Ca phase has a high melting point (1075°C) with good creep resistance [34], and these characteristics are believed to stabilize the shape of reinforcement filaments against spheroidization and coarsening that can cause degradation of both strength and conductivity [16]. The Al$_4$Ca peak has a lower magnitude of enthalpy of formation (-43.9±4.2 kJ/mol) than Al$_2$Ca (-73.2±4.2 kJ/mol), contributing to the smaller exotherm of the former [17]. Table 4 shows that the temperature at which the Al$_2$Ca event peak occurs is lower for wires with greater strain likely because the smaller filament spacing creates a shorter diffusion path for the formation of the intermetallic compound and greater Gibbs-Thomson curvature effect [16]. A prominent peak for the
formation of Al₄Ca is seen only in samples with high strain (η>9.5), since Al₄Ca can be formed quickly at clean interfaces resulting from mechanical working [35] before being consumed in the transformation to Al₂Ca. Wires with larger filament spacing do not inter-diffuse rapidly enough at the high heating rate used to form an isolated Al₄Ca intermetallic phase at the temperature seen for smaller wires (220°C), and the two event peaks begin to merge. Further study of the activation energy for diffusion of each atom type into the other is necessary to better understand the kinetics of the intermetallic phase formation.

**Table 4.** Al₂Ca DSC peak maximums for various deformation true strain levels.

<table>
<thead>
<tr>
<th>η</th>
<th>Max Temp (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>11.5</td>
<td>264</td>
</tr>
<tr>
<td>9.67</td>
<td>269</td>
</tr>
<tr>
<td>8.41</td>
<td>269</td>
</tr>
</tbody>
</table>

Based on the results from Table 4, small pieces of select wires were sealed under argon and heat treated in a furnace at 260°C for the times specified in Table 3. The objective was to transform the Ca filaments to Al₂Ca but without excessive exposure to high temperature. Doing so could potentially lead to diffusion along the interface creating sinusoidal perturbations, giving a “string of pearls” morphology [7]. DSC tests were done on these wires that underwent a “flash” heat treatment to confirm the completion of reinforcement phase transformation seen in the suppression of the exothermic peaks as shown by Figure 14.
Based on these results it appears that the smaller wires were fully transformed, while the largest sample still had trace amounts of pure Ca in the reinforcement filaments. After transformation to intermetallic reinforcement, the wire microstructure becomes more stable, making it resilient (highly resistant to Joule heating effects), even during emergency overloading. These DSC results were used in conjunction with microstructural analysis to determine an appropriate heat treatment schedule for the array of wires to be used for further testing.

4.3 Microstructural analysis of Al/Ca (11.5 vol.%) and Al/Al₂Ca (18 vol.%) composites

The microstructures of DMMCs have been studied in great detail in the past several decades [4, 7, 36] and in recent years for the Al/Ca composite system [5, 6, 22]. This section will be broken into two parts that further study the microstructure of these materials. The first will examine the microstructure of Al/Ca composites in their as-drawn state and also look at the effect of converting
the filaments with the short heat treatment previously described. The second part will look at the microstructure after prolonged exposure to elevated temperatures.

4.3.1 Microstructure: As-drawn and converted Al/Ca composites

Figure 15 shows that the “swirled” ribbon-shaped morphology seen in the prior generation of Al/Ca composite exists at lower strain levels, but it is altered by extensive mechanical working. The resultant morphology is in contrast to the expectations of classic composite morphology theory that predicts cylindrical filaments due to axi-symmetrical deformation for a fcc secondary phase in a fcc matrix. A possible explanation is a temporary crystal structure transformation in Ca from fcc to bcc during extrusion that leads to plane-strain deformation giving rise to the ribbon-like shape [5, 6, 7], but this has not been further explored in this study.

![Figure 15. Backscattered electron micrographs of Al/Ca (11.5 vol.%) composite transverse cross section with pure Ca filaments: (a) η=6.74, (b) η=9.67.](image)

With conversion of Ca filaments to Al$_2$Ca, the microstructure undergoes changes that have a direct impact on the performance properties of the material. Figure 16 shows the transverse view of wires at two different magnifications that underwent filament transformation.
In comparing Figures 15 and 16, it is difficult to see the effects of the filament transformation process. By looking at the longitudinal cross-section instead this change becomes more apparent. Figure 17 shows evidence of change in the reinforcement filaments in the longitudinal direction. The Ca second phase displays a long continuous morphology with nearly uniform thickness. During swaging or drawing, the filament size decreases exponentially by a factor directly related to the reduction in the overall wire cross section according to Equation 1. Filaments are able to deform with a consistent thickness since Al and Ca have nearly equal flow stresses, avoiding problems with a softer phase flowing around a harder second phase [7, 37]. Filament size

Figure 16. Backscattered electron micrographs of Al/Ca (18 vol.%) composite transvers cross section with converted filaments at two magnifications: (a/c) $\eta=6.74$, (b/d) $\eta=9.67$. 
and spacing are critical parameters that affect the performance of DMMCs and allow comparison of small, lab-scale specimens to potential full-size extrusions on the basis of true strain.

The conversion process results in Al$_2$Ca filaments that appear brighter in the micrographs shown. One critical concern with the heat treatment process is spheroidization that can lead to breaking of filaments that degrades mechanical and electrical properties. Based on micrographs at various strain levels, it appears that this did not occur to a significant extent during the heat treatment period, and the filaments remained intact. Longer term exposure to elevated temperatures is a matter of interest and will be discussed further.

Figure 17. Backscattered electron micrographs of Al/Ca (11.5 vol.%) composite longitudinal cross section at $\eta=9.67$: (a) pure Ca filaments, (b) Al$_2$Ca reinforcement after heat treatment.

One of the intended consequences of transformation was the growth of the secondary phase from 11.5 vol.% Ca to 18 vol.% Al$_2$Ca. The micrographs in Figure 17 clearly show a change in the filament size (dia.) with a measured increase in thickness from 0.9$\mu$m to 1.5$\mu$m for the selected strain level. This difference is very close to what is expected indicating that the transformation to Al$_2$Ca is essentially complete, as confirmed by DSC and XRD [5, 6]. Figure 18 shows additional longitudinal cross-sections at a lower strain level for comparison. At the two levels of magnification shown, it appears as if the transformation is complete and the filaments are relatively straight.
As reported here, DSC and SEM confirmed that the transformation was completed but not excessive, enabling the study of modified performance properties. The next part will discuss changes to the microstructure that occur as a result of extended heat treatments.

4.3.2 Microstructure: Extended heat treatment

Concerns about the long-term stability of Al/Ca composites drove the decision to intentionally convert the reinforcement material to Al$_2$Ca. Therefore, it is important to study how the microstructure and properties of the material evolved as a result of prolonged exposure to elevated temperatures. The samples that were already converted were further heated in a vacuum.
furnace at 150 and 200°C for periods ranging from 4 hours to 1 week. The corresponding micrographs for wires with moderate deformation treated at 200°C are shown in Figure 19.

*Figure 19.* Backscattered electron micrographs of Al/Al$_2$Ca (18 vol.%) at 6.74 after heat treatment at 200°C for: (a) 0 hours, (b) 4 hours, (c) 45 hours.
It is clear that after extended periods, the long and continuous filaments begin to break up and develop a more complex morphology. This spheroidization and coarsening was expected based on previous research [7, 15, 30], but the effect that it has on Al/Ca composite properties has not yet been well studied. The following sections will discuss the electrical conductivity and tensile strength of these materials, both of which are extremely important for the intended application. The effects that converting filaments to an intermetallic species and extended heat treatments have on these properties were also investigated.

4.4 Electrical conductivity of Al/Ca (11.5 vol.%) and Al/Al2Ca (18 vol.%) composites

Given that the intended application of Al/Ca composites is high-voltage power transmission, conductivity is a critical property in evaluating the commercial viability of such conductors. The primary advantage of this material is the absence of a highly resistive steel core needed for strength in conventional conductors (ACSR). This monolithic construction allows for high conductivity across the entire cross section of the conductor with the direction of current flow being parallel to the filaments. The conductivity will be examined in as-drawn, converted, and wires with long exposure time to high temperature.

4.4.1 Electrical conductivity: As-drawn and converted Al/Ca composites

Figure 20 shows results for conductivity measurements on both unconverted wires and those that have been transformed at various strain levels. The error bars shown include the propagation of all relevant measurement errors, including wire size, making the value for smaller wires less certain.
Figure 20. Electrical conductivity of third-generation Al/Ca (11.5 vol.%) composite before and after transformation of filaments to Al$_2$Ca intermetallic at various strain levels.

At low strain levels the conductivity is very close to the rule of mixtures prediction for the given formulation since current flows across the entire cross section and the filament size is significantly larger than the mean free path of electrons. Tian et al have studied the numerous scattering mechanisms in DMMCs and shown that by reducing the filament thickness and spacing, there is an increase in interface and grain boundary scattering that reduces the conductivity of the material [38]. These mechanisms have been shown to exist in previous generations of Al/Ca composite [6] and are clearly present here.

The effect on conductivity of the transformation of the filaments to Al$_2$Ca is evident, i.e., a diminished value, but the diminution was found to be small. For the wires subjected to the greatest level of deformation in this study ($\eta=12.7$), the measured drop in conductivity is less than 1%.
Al/Ca (20 vol.%) showed similar behavior as the material in this study for unconverted wires but displayed severe degradation after heat treatment [6]. This drop off in conductivity can be attributed to a large fraction (32 vol.%) of the cross section being occupied by Al$_2$Ca after transformation. With the reduced loading of Ca in Al/Ca (11.5 vol.%), the transformation has a less substantial impact on the increase in interfacial area, and therefore the influence of interface scattering is not greatly affected. Even with this consideration, the very slight reduction that does not agree with (is well above) the ROM expectation for Al/Al$_2$Ca (18 vol.%) is a pleasant surprise. This minimal decrease in conductivity seems a worthwhile sacrifice in exchange for the high-temperature stability that the intermetallic phase could potentially provide. With complete transformation to Al$_2$Ca, the composite conductor material could have an increased upper use temperature, making it resilient even during emergency overloading situations [16].

4.4.2 Electrical conductivity: Extended heat treatment

As shown in the previous section, the microstructure undergoes significant change after heat treatment at 200°C. The filaments break up causing an increase in interfacial area between the Al$_2$Ca filaments and the aluminum matrix. This increase in area is in excess of what is caused by the initial conversion of the reinforcement to an intermetallic and is more difficult to quantify. Figure 20 showed that the modest increase in filament size had a small effect on the electrical conductivity since the filaments still remained straight and continuous. Figure 21 shows the electrical conductivity of samples that were exposed for various combinations of time, temperature, and atmosphere (air or vacuum) and includes the results from Figure 20 for comparison. The highest strain levels are not reported due to the inability to test finer wires that were more brittle than before aging.
Figure 21. Electrical conductivity of third-generation Al/Ca (11.5 vol.%), composite before and after transformation of filaments to Al$_2$Ca intermetallic at various strain levels with extended heat treatment samples.

It is clear that the electrical conductivity of converted wires is reduced as a result of all of the different heat treatment conditions used. There are several things that can be inferred from these results including the fact that it did not make a significant difference whether wires were heated in the presence of air or not. This indicates that the mechanism of degradation is not due to oxidation along the filaments. Additionally, from the small number of conditions tested, it appears that the conductivity will reach a minimum independent of the temperature at which the wires are aged. The implication of this finding is that this is a time dependent process that can be designed for or controlled. Knowing that the material will reach an endpoint in terms of conductivity, the amount of initial calcium loading and the amount of strain imparted on the sample can be managed to give the properties that are desired. Given that the electrical conductivity is a function of at least these two
parameters, it is also important to examine how changing them affects other properties of the material such as the tensile strength.

4.5 Tensile strength of Al/Ca (11.5 vol.%) and Al/Al2Ca (18 vol.%) composites

While decreasing the filament size by mechanical working lowers the conductivity of the composite, the primary motivation for doing this is to benefit from the unique strengthening mechanism of DMMCs. The Al/Ca (11.5 vol.%) composite had a reduced loading of Ca to facilitate the volume expansion of filaments upon transformation to Al$_2$Ca but, it has been shown that there is an additional increase in interfacial area beyond this expansion after prolonged heat treatment. The tensile strength has been investigated for various strain levels because the strength increases exponentially as a function of reduced filament spacing in these materials [4, 7, 15]. The effect of converting filaments to Al$_2$Ca reinforcement and thermal aging of wires has again been studied.

4.5.1 Tensile Strength: As-drawn and converted Al/Ca composites

Figure 22 shows representative stress-strain curves for Al/Ca (11.5 vol.%) and converted Al/Al$_2$Ca (18 vol.%) composites from tensile testing of 0.2 mm wires (η=11.5).
Figure 22. Stress-strain curves for 0.2mm (η=11.5) Al/Ca (11.5 vol.%) and Al/Al$_2$Ca (18 vol.%).

It is evident from the tensile test curves in Figure 22 that samples with intermetallic reinforcement fibers have superior strength to unconverted wires for this given level of deformation true strain. These trends are representative of other wires sizes that showed very similar behavior with increasing strength and apparent retention of ductility. Figure 23 shows the fracture surfaces corresponding to the wires that underwent tensile testing depicted in Figure 22.

Figure 23. Fracture surfaces of 0.2mm (η=11.5) tensile specimen: (a) pure Ca filaments, (b) Al$_2$Ca reinforcement after heat treatment.
The fracture surfaces seen in Figure 23 exhibit classic dimples in the Al matrix typical of fibrous ductile fracture [15]. Surprisingly, the composite still demonstrates ductile behavior after conversion to intermetallic reinforcement even while achieving increased ultimate tensile strength. This could be very beneficial during both operation and winding of the conductor. The wires with the highest level of deformation true strain ($\eta=12.7$) were independently tested by Psylotech with the results shown in Figure 24.

![Figure 24. Stress-strain curve for ten 0.1mm ($\eta=12.7$) wires (a) five of which were unconverted, and (b) five of which had been converted.](image)

Again, it is shown that converting the reinforcement phase results in a higher strength. In addition to the results shown in Figure 22 and Figure 24, various other size wires were tested to determine their ultimate tensile strength. Figure 25 shows the exponential relationship between deformation true strain and UTS for as-drawn and converted wire samples at various strain levels with comparison to other conductors that would be suitable for HVDC transmission. The existing commercial wires used for comparison are shown in Table 1.
Figure 25. Tensile strength of Al/Ca (11.5 vol.%) and Al/Al$_2$Ca (18 vol.%) with Hall-Petch model fitting.

The influence of filament size and fractional loading suggests that interfacial area plays a major role in strengthening the composite. Study of early DMMCs had shown that interphase boundaries act as barriers to dislocation glide leading to interface strengthening [4]. This effect causes strength to increase sharply at high strains, which has been successfully modeled by a modified Hall-Petch barrier model for previous Al/Ca composites [5, 6, 22]. Based on measurements of filament thickness, the dependence on true strain was assumed to be ideal following the relationship of Equation 6 where $d_o$ is the starting Ca size.

$$t = d_o e^{-\frac{1}{2\eta}}$$ (6)
Using the calculated thickness from Equation 6 and the measurements of UTS, Hall-Petch relationships were determined for both as-drawn and transformed wires shown by Equations 7 and 8, respectively.

\[ UTS = -10.7 + \frac{148.0}{\sqrt{\varepsilon}} \]  
(7)

\[ UTS = 32.3 + \frac{146.8}{\sqrt{\varepsilon}} \]  
(8)

The evident strengthening effect from conversion of the reinforcement phase to intermetallic was expected due to the increase in interfacial area upon volume expansion of the filaments. It has been shown that both the material and composition of the reinforcement phase in aluminum matrix DMMCs influence the ultimate tensile strength of the composite [5, 13, 12]. When compared to Al/Ca (20 vol.%) and Al/Ca (11.5 vol.%), it appears that the filaments being comprised of Al\(_2\)Ca rather than Ca has little effect, and the volume of reinforcement is the dominant factor. The curves for these wires have a very similar shape and differ by an offset for most strain levels. This direct comparison of as-drawn and transformed wires however, fails to account for the impact of volume expansion on the effective true strain, but the heat-treatments are likely to reduce dislocation densities to low values. Measurements of the wire cross-section from SEM micrographs for various wire sizes indicate that the expansion of filaments does not appreciably change the overall dimension. The consequence of this finding is that the filament thickness calculated by Equation 6 needs to be adjusted by a factor related to the volume expansion of the filaments. By implementing this change, the effective true strain is reduced, and the measured strength values are shifted to the left as shown in Figure 26.
Figure 26. Tensile strength of Al/Ca (11.5 vol.%) and Al/Al$_2$Ca (18 vol.%) with true strain adjustment.

The major takeaway from analyzing the tensile strength with this adjustment is that Al$_2$Ca is a more effective reinforcement material than pure Ca. At high effective true strain levels ($\eta$>11), Al$_2$Ca-reinforced composite is expected to be stronger than Al/Ca wires containing a greater reinforcement fraction (higher than Al/Ca (20 vol.%)). Further study of the material properties of the Al$_2$Ca compound is necessary in order to utilize more advanced modeling techniques that incorporate the individual contributions from each phase to predict the strength [39]. From a practical standpoint, comparing unconverted and transformed wires on the basis of effective true strain is not ideal, as this would necessitate a larger starting extrusion billet size for converted wires that are of the same size. For composites including two ductile phases such as the Al/Ca system,
strains as high as 16 can be reached without fracturing, but in so doing one must be mindful of the need to balance the tradeoff between strength and conductivity. Figure 27 shows the relationship between strength and conductivity for converted wires of the highest strain level tested in this study. This figure uses specific strength to highlight the benefit of reduced weight in Al/Ca composites.

![Figure 27](image)

*Figure 27. Summary of specific strength and electrical conductivity of Al/Al\textsubscript{2}Ca composites and commercial conductor technologies.*

Having lower weight is advantageous for overhead conductors since it enables larger conductors or increased tower spacing. In addition to these considerations, the highest attainable strain level seems to be dictated mainly by the starting billet size and ram force of the commercial extrusion capabilities that are available. One potential option to be explored is sectioning and bundling of the extrudate then extruding a second time in order to achieve smaller filament spacing.
4.5.2 Tensile strength: Extended heat treatment

Just as the microstructural changes resulting from thermal aging affect the electrical conductivity, they also affect the strength of converted Al/Al$_2$Ca composites. Figure 28 shows the strength at room temperature of wires that were aged for 4 and 45 hours at 200°C and 1 week at 150°C. Only samples that were aged in vacuum conditions were tested since it was found that they were not significantly different from those heated in air. Also, the highest strain ($\eta=12.7$) samples were not tested due to resource limitations.

![Graph showing tensile strength](image)

*Figure 28. Tensile strength of Al/Al$_2$Ca after extended heat treatments.*

It is clear that strength is reduced by long term exposure to elevated temperature. Similar to the results for electrical conductivity, differences in aging temperature and time did not have a significant effect on the results. Although the strength of these samples was reduced, it was still greater than that of the unconverted wire for all strain levels. Similar to the modification of the
deformation true strain that was made in the previous section to account for the volume expansion upon conversion of filaments, the strength values could be shifted based on their increased interfacial area from the break-up and coarsening of filaments. This is difficult to quantify in a definitive manner due to the irregular shape of the reinforcement after aging but, it could help guide future formulations since the curves would again be shifted further to the left as in Figure 26.
CHAPTER 5. Al/Ca COMPOSITE PERFORMANCE CASE STUDY

The effects of the reinforcement fraction and level of deformation on strength and conductivity have been discussed, and the tradeoff between the two is evident. This chapter will explore how the properties determined in Chapter 4 would provide benefits relative to conventional aluminum-conductor steel-reinforced (ACSR) materials. This analysis will use properties of converted Al/Al$_2$Ca (18 vol.%) composites with $\eta=12.7$, but the framework presented could be applied to other formulations and strain levels.

5.1 Conditions

As discussed in Chapter 2, Al/Ca composite materials show promise for commercial adoption as overhead conductors. Therefore, it was decided to study the Pacific DC Intertie (Path 65), an existing HVDC transmission line in the western United States shown in Figure 29 [40].

![Pacific DC Intertie map](image)

*Figure 29. Pacific DC Intertie map.*

Using this existing system with the properties summarized in Table 5 [41], Al/Ca materials’ performance can be compared to conventional ACSR conductors’ performance. The comparison of
the two was completed for two different cases including reconductoring on existing towers and a new installation with varied tower spacing. The conditions that were kept constant and varied in order to make this comparison are shown in Table 6.

Table 5. Pacific DC Intertie line conditions specifications.

<table>
<thead>
<tr>
<th>Total Distance</th>
<th>846 miles</th>
</tr>
</thead>
<tbody>
<tr>
<td>Conductor Cross Section</td>
<td>1171 mm² (Bluebird)</td>
</tr>
<tr>
<td>Voltage</td>
<td>±500 kV</td>
</tr>
<tr>
<td>Rated Power</td>
<td>3100 MW</td>
</tr>
<tr>
<td>Number of Towers</td>
<td>4200</td>
</tr>
<tr>
<td>Current</td>
<td>3100 A</td>
</tr>
</tbody>
</table>

Table 6. Scenarios for case study.

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Constant with base case</th>
<th>Varied</th>
</tr>
</thead>
<tbody>
<tr>
<td>ACSR</td>
<td>As built</td>
<td>As built</td>
</tr>
<tr>
<td>Case 1</td>
<td>Tower spacing and weight per tower</td>
<td>Conductor Size</td>
</tr>
<tr>
<td>Case 2</td>
<td>Losses and weight per tower</td>
<td>Tower spacing and Conductor Size</td>
</tr>
</tbody>
</table>

In order to evaluate the size, installation conditions, and performance of Al/Ca composite conductors, several properties needed to be determined. The temperature of the conductor as a function of the current is important because conductors have upper operating limits [42, 43, 44]. Determination of this relationship was done according to the IEEE-738 standard and allowed for specification of the ampacity [42]. Another critical parameter for designing overhead transmission lines is the sag resulting from thermal expansion or added loading. This was determined by the numerical sag method (NSM) for initial stranding, high temperature, and wind and ice conditions as specified by the National Electrical Safety Council (NESC) [43, 44].
5.2 Case 1 Results

Case 1 considers a direct replacement of the transmission line using the same towers and assumes equal spacing for the ruling span. Additionally, it is assumed that the tower will only support the same conductor weight per tower. Figure 30 shows the relationship between current and temperature for the Al/Al₂Ca and ACSR conductors. The conditions used as inputs for IEEE-738 to determine this relationship are shown in Appendix 1.

It is clear that under the assumed conditions Al/Al₂Ca conductors would operate at a slightly lower temperature for a given current. This is mainly due to the fact that the cross-sectional area is larger, which is enabled by Al/Ca’s lower density. From an operational standpoint, using a different material that has a similar ampacity would not result in any significant change. The primary difference comes in the vertical sag of the conductor as shown by Figure 31.
The sag of Al/Al$_2$Ca is lower because of a combination of higher strength and lower density. The upper temperature limit of a traditional conductor is typically limited by the thermal sag [43] so being able to achieve both of these properties simultaneously is advantageous. The NESC heavy condition for wind and ice loading was used to design the conductor for this case study. Table 7 shows the sag at these conditions in addition to the size of the conductor and other related results.

Table 7. Case 1 conductor properties.

<table>
<thead>
<tr>
<th></th>
<th>ACSR</th>
<th>Case 1</th>
</tr>
</thead>
<tbody>
<tr>
<td>Conductor diameter</td>
<td>mm</td>
<td>44.8</td>
</tr>
<tr>
<td>Conductor Area</td>
<td>mm$^2$</td>
<td>1181</td>
</tr>
<tr>
<td>Temperature at Max Amps</td>
<td>ºC</td>
<td>79</td>
</tr>
<tr>
<td>Sag at Peak Amps</td>
<td>m</td>
<td>9.22</td>
</tr>
<tr>
<td>Wind/Ice Total Sag</td>
<td>m</td>
<td>7.25</td>
</tr>
<tr>
<td>Wind/Ice %Rated Tensile Strength</td>
<td>%</td>
<td>42.7</td>
</tr>
</tbody>
</table>

Figure 31. Case 1 sag compared to ACSR.

![Graph showing sag comparison between ACSR Bluebird and Case 1 Al/Al$_2$Ca conductors.](image)

The sag of Al/Al$_2$Ca is lower because of a combination of higher strength and lower density.
One important parameter to point out is that a maximum rated temperature of 120°C was assumed for the design of this conductor. This was not of great significance in this case since the conductor size used would operate well below that point, and sag does not appear to be a major concern for the existing tower spacing. Since the use of larger conductors is enabled by high strength and low density, the benefit of Al/Al₂Ca for this case is a reduction in electrical losses from Joule heating as shown by Figure 32.

![Figure 32. Case 1 electrical losses compared to ACSR.](image)

Over the long span that is used in this case, and is typical of HVDC transmission lines, this reduction in electrical losses is very substantial. Even though the performance is improved for this case, the conditions are not ideal because the conductor is limited by size rather than sag or ampacity.
5.3 Case 2 Results

The results from Case 1 showed that replacing an existing line with Al/Ca composite conductors can provide significant benefits, even though the system was not specifically designed for their use. This case will show the benefits of using these materials with the tower spacing and conductor size being optimized for use on support towers that can hold the same load as the ACSR base case. Again, the ampacity was determined from the conditions summarized in Appendix 1 and compared to that of the existing ACSR conductor as shown in Figure 33.

As with Case 1, the temperature of the conductor would be slightly lower for a given current, but the difference is less pronounced. The major difference is that the tower spacing was optimized so that at the maximum allowable temperature value specified, the sag of the conductor was equal to a maximum sag value. Figure 34 shows the relationship between temperature and sag for this case and also includes ACSR for comparison.
The sag has a linear relationship with temperature since the conductor is constructed with a single material. ACSR also appears to be linear due to the fact that the maximum rated operating temperature is below the knee point of the conductor \([43]\). The accuracy of the conductor design in this case would be improved by further study of the upper operating temperature of Al/Ca conductors. Table 8 shows the conductor dimensions in addition to the sag values at the limiting conditions.
Table 8. Case 2 conductor properties.

<table>
<thead>
<tr>
<th></th>
<th>ACSR</th>
<th>Case 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Conductor diameter</td>
<td>mm</td>
<td></td>
</tr>
<tr>
<td>Conductor Area</td>
<td>mm²</td>
<td></td>
</tr>
<tr>
<td>Weight per unit length</td>
<td>lb/ft</td>
<td></td>
</tr>
<tr>
<td>Temperature at Max Amps</td>
<td>°C</td>
<td></td>
</tr>
<tr>
<td>Sag at Peak Amps</td>
<td>m</td>
<td></td>
</tr>
<tr>
<td>Max Temperature</td>
<td>°C</td>
<td></td>
</tr>
<tr>
<td>Sag at Max Temperature</td>
<td>m</td>
<td></td>
</tr>
<tr>
<td>Wind/Ice Total Sag</td>
<td>m</td>
<td></td>
</tr>
<tr>
<td>Wind/Ice %RTS</td>
<td>%</td>
<td></td>
</tr>
<tr>
<td>Conductor diameter</td>
<td></td>
<td>44.8</td>
</tr>
<tr>
<td>Conductor Area</td>
<td>mm²</td>
<td>1181</td>
</tr>
<tr>
<td>Weight per unit length</td>
<td>lb/ft</td>
<td>3736</td>
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<tr>
<td>Temperature at Max Amps</td>
<td>°C</td>
<td>79</td>
</tr>
<tr>
<td>Sag at Peak Amps</td>
<td>m</td>
<td>9.22</td>
</tr>
<tr>
<td>Max Temperature</td>
<td>°C</td>
<td>100</td>
</tr>
<tr>
<td>Sag at Max Temperature</td>
<td>m</td>
<td>10</td>
</tr>
<tr>
<td>Wind/Ice Total Sag</td>
<td>m</td>
<td>7.25</td>
</tr>
<tr>
<td>Wind/Ice %RTS</td>
<td>%</td>
<td>42.7</td>
</tr>
</tbody>
</table>

Table 8 shows that the conductor used for this case is slightly larger than the existing ACSR material. Even with a larger diameter, the support towers are able to be spread farther apart because of the higher strength and lower density that Al/Al₂Ca possesses. Figure 35 shows that the number of towers required is reduced while achieving equivalent electrical losses to the existing material.

Figure 35. Case 2 towers required compared to ACSR.
Spacing towers further apart would likely not be done for an existing line but new installations could benefit from the advantage that this provides. Towers and their associated engineering, installation, and right-of-way costs can contribute a significant amount (as much as 50%) to the total cost of a transmission project so eliminating towers would be a great benefit.

It has been shown that using Al/Al₂Ca composite conductors in place of conventional ACSR steel-core conductors can provide benefits in terms of both initial investment and long-term costs. The properties of these materials can be tailored through intelligent formulation and processing to meet the needs of a specific application. The calculations presented in this chapter can easily be applied to other formulations and different existing conductors in order to quantify the benefits of using a certain material.
CHAPTER 6. CONCLUSIONS

- An Al/Ca (11.5 vol.%) composite with nanofilamentary reinforcement was produced by powder metallurgy and deformation processing to a maximum true strain of 12.7.

- Differential scanning calorimetry identified the temperature at which Al₄Ca and Al₂Ca intermetallic compounds are formed and the dependence on true strain for these events.

- SEM micrographs showed similar ribbon-shaped filaments seen in prior generations of Al/Ca composite and the development of a complex morphology after extensive deformation processing.

- After transformation of the reinforcement phase, volume expansion occurred producing Al/Al₂Ca (18vol.%) composite. Longitudinal micrographs revealed no significant filament coarsening or spheroidization after initial conversion.

- The electrical conductivity decreased with reduced filament spacing at high true strains. The transformation of filaments to Al₂Ca caused the conductivity to drop by less than 5% for wires subjected to the greatest level of deformation in this study (η=12.7).

- The ultimate tensile strength of as-drawn Al/Ca (11.5vol.%) composite increased with deformation true strain due to the strong influence of interface strengthening, which is well described by a modified Hall-Petch barrier model. The UTS increased upon transformation of the secondary phase due to the increase in interfacial area and presence of a stronger reinforcement phase, but retention of a remarkable ductility also was found, even in the strongest wires.

- Extended thermal aging of wires resulted in the breakup of filaments and a modified microstructure. These changes led to decrease in both electrical conductivity and tensile strength.
• Preliminary line sizing calculations indicate that the use of Al/Al\(_2\)Ca conductors in place of ACSR could reduce electrical losses by 11.1% for existing tower spacing or reduce the number of towers by 12.4% for the same losses.

• Al/Al\(_2\)Ca composite wires show promise to exhibit strength superior to current conductor technologies combined with high electrical conductivity, low density, and high temperature performance making them excellent candidates for use as HVDC transmission conductors.
CHAPTER 7. RECOMMENDATIONS FOR FUTURE WORK

• A principal barrier to full strengthening of Al/Ca composites is the availability of fine Ca metal powder for co-extrusion with Al powder to reduce the final filament size to that needed to achieve high strength. Ca powder surfaces must be passivated through the use of an oil quenchant bath or an in-flight reaction gas spray. For adaption to commercial atomizers, the reaction gas method is preferred so development of this technology is required. An induction melting passivation system (IMPASS) that was successfully utilized to develop a passivation technique for Mg powder can be used for preliminary tests prior to deployment in Ames Lab’s centrifugal atomizer with a rotating quench bath (CARQB). Several reaction gases should be tested including SF₆ and other alternative fluorinated gases.  

• Laboratory samples were produced with high-purity aluminum powder supplied by Ames Laboratory. In order to ensure the same “clean” microstructure in commercial-scale production, Al with low oxide content must be used. This will require working with a corporate partner to improve their practices in producing Al of pigment quality in the appropriate size.  

• Now that the concept of intentionally converting the reinforcement phase to Al₂Ca intermetallic has been proven, further confirmation of test results is necessary from industrial conductor companies. In addition, a full industrial prototype extrusion billet should be produced in order to provide enough wire for a complete conductor of sufficient length to test at Oak Ridge National Laboratory’s (ORNL) Powerline Conductor Accelerated Testing (PCAT) facility. This task will require the successful completion of the other tasks mentioned previously.  

• In addition to the tasks described that will enable commercialization of Al/Ca conductors, further study of the transformation of Ca filaments to Al₂Ca is required. The effects of long-
term heat treatments need to be better understood in order to assess the upper temperature limit of the material. Also, these studies will help guide the decision of the appropriate amount of calcium and deformation level in the production of future samples.
REFERENCES


### APPENDIX. AMPACITY AND SAG CALCULATION PARAMETERS

<table>
<thead>
<tr>
<th>Condition</th>
<th>Clear</th>
<th>Case 1</th>
<th>Case 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>$H_e$  Elevation of conductor above sea level</td>
<td>m</td>
<td>0</td>
<td>Al/Al$_2$Ca</td>
</tr>
<tr>
<td>Lat   Degrees of latitude</td>
<td>degrees</td>
<td>30</td>
<td>Al/Al$_2$Ca</td>
</tr>
<tr>
<td>N     Date (M/DD/YY)</td>
<td>—</td>
<td>42896</td>
<td></td>
</tr>
<tr>
<td>$T_a$  Ambient air temperature</td>
<td>°C</td>
<td>35</td>
<td></td>
</tr>
<tr>
<td>$V_w$  Speed of air stream at conductor</td>
<td>m/s</td>
<td>0.61</td>
<td></td>
</tr>
<tr>
<td>$Z_l$  Azimuth of line</td>
<td>degrees</td>
<td>90</td>
<td></td>
</tr>
<tr>
<td>$\alpha$ Solar absorptivity (0.23 to 0.91)</td>
<td>—</td>
<td>0.5</td>
<td></td>
</tr>
<tr>
<td>$\varepsilon$ Emissivity (0.23 to 0.91)</td>
<td>—</td>
<td>0.5</td>
<td></td>
</tr>
<tr>
<td>$\varphi$ Angle between wind and axis of conductor</td>
<td>degrees</td>
<td>90</td>
<td></td>
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<tr>
<td>$\omega$ Time (HH:MM:SS AM)</td>
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<td>0.375</td>
<td></td>
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<td>Wind and Ice Conditions</td>
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<tr>
<td>Constant</td>
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<td>Ice Density</td>
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<td></td>
<td>Al/Al$_2$Ca</td>
</tr>
<tr>
<td>$T_c$  Minimum Temperature</td>
<td>°C</td>
<td>50</td>
<td>50</td>
</tr>
<tr>
<td>$T_{max}$ Maximum Operating Temperature</td>
<td>°C</td>
<td>150</td>
<td>150</td>
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<tr>
<td>$D$   Conductor diameter</td>
<td>mm</td>
<td>48.92</td>
<td>46.12</td>
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<td>$T_{low}$ Minimum temp dc resistance is specified</td>
<td>°C</td>
<td>20</td>
<td>20</td>
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<td>$T_{high}$ Maximum temp dc resistance is specified</td>
<td>°C</td>
<td>75</td>
<td>75</td>
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<tr>
<td>$R(T_{low})$ DC resistance at Tlow</td>
<td>Ω/m</td>
<td>2.38E-05</td>
<td>2.68E-05</td>
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<td>$R(T_{high})$ DC resistance at Thigh</td>
<td>Ω/m</td>
<td>2.86E-05</td>
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<td>$w$   Weight per unit length</td>
<td>lb/ft</td>
<td>2.51E+00</td>
<td>2.23E+00</td>
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<tr>
<td>I     Span</td>
<td>ft</td>
<td>1063</td>
<td>1196</td>
</tr>
<tr>
<td>$\alpha_{cond}$ Coefficient of Thermal Expansion</td>
<td>/°C</td>
<td>2.20E-05</td>
<td>2.20E-05</td>
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<td>$T_{max}$ Maximum Operating Temperature</td>
<td>°C</td>
<td>120</td>
<td>120</td>
</tr>
<tr>
<td>$T_{min}$ Initial Sag Temperature (Stringing)</td>
<td>°C</td>
<td>15.5</td>
<td>15.5</td>
</tr>
<tr>
<td>$E$   Elastic Modulus</td>
<td>Psi</td>
<td>9177477</td>
<td>9177477</td>
</tr>
<tr>
<td>$A$   Conductor Area</td>
<td>in$^2$</td>
<td>2.185</td>
<td>1.942</td>
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<td>$E_c$ Plastic Deformation</td>
<td>ft/ft</td>
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<td>Strength</td>
<td>lbf</td>
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<td>%RBS  % Rated Break Strength at installation</td>
<td>%</td>
<td>25</td>
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<tr>
<td>weight/tower</td>
<td>lbs</td>
<td>2668</td>
<td>2668</td>
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<tr>
<td>-------------</td>
<td>-----</td>
<td>------</td>
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</tr>
<tr>
<td>Area</td>
<td>mm²</td>
<td>1410</td>
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<td>number of towers</td>
<td></td>
<td>4201</td>
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<tr>
<td>total span</td>
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<td>4465223</td>
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<tr>
<td>total weight</td>
<td>lbs</td>
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**Initial Sag/Tension at Stringing Temperature**

<table>
<thead>
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<th>°C</th>
<th>15.5</th>
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<tr>
<td>Total Initial Tension at Stringing Temp</td>
<td>lbs</td>
<td>28697.7</td>
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<td>Sag at Initial Stringing Temperature</td>
<td>m</td>
<td>3.8</td>
<td>4.77</td>
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**Sag at Peak Operating Amps**

<table>
<thead>
<tr>
<th>Temperature at Max Amps</th>
<th>°C</th>
<th>70.36</th>
<th>75.16</th>
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<tbody>
<tr>
<td>Total Tower Tension at Max Amps</td>
<td>lbs</td>
<td>19798.0</td>
<td>18010.3</td>
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<tr>
<td>Sag at Peak Amps</td>
<td>m</td>
<td>5.46</td>
<td>6.75</td>
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</table>

**Sag at Max Operating Temperature**

<table>
<thead>
<tr>
<th>Max Temperature</th>
<th>°C</th>
<th>120</th>
<th>120</th>
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</thead>
<tbody>
<tr>
<td>Total Tower Tension at Max Temp</td>
<td>lbs</td>
<td>12650.7</td>
<td>12173.2</td>
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<tr>
<td>Sag at Max Temperature</td>
<td>m</td>
<td>8.54</td>
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**Temperature/Ampacity at Max Sag**

<table>
<thead>
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<tr>
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<td>10806.1</td>
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</tr>
<tr>
<td>Sag</td>
<td>m</td>
<td>10.00</td>
<td>10.00</td>
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<tr>
<td>Ampacity at Max Sag</td>
<td>A</td>
<td>2942.8</td>
<td>2305.3</td>
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</table>

**Wind/Ice or Cold Temperature Sag**

<table>
<thead>
<tr>
<th>Total Tower Tension</th>
<th>lbs</th>
<th>45925.6</th>
<th>41562.9</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total Sag</td>
<td>m</td>
<td>4.16</td>
<td>5.36</td>
</tr>
<tr>
<td>Vertical Sag</td>
<td>m</td>
<td>3.77</td>
<td>4.81</td>
</tr>
<tr>
<td>%RTS</td>
<td>%</td>
<td>40.01</td>
<td>40.74</td>
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