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Deformation processed Al/Ca nano-filamentary composite conductors for HVDC applications

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Abstract. Efficient long-distance power transmission is necessary as the world continues to implement renewable energy sources, often sited in remote areas. Light, strong, high-conductivity materials are desirable for this application to reduce both construction and operational costs. In this study an Al/Ca (11.5% vol.) composite with nano-filamentary reinforcement was produced by powder metallurgy then extruded, swaged, and wire drawn to a maximum true strain of 12.7. The tensile strength increased exponentially as the filament size was reduced to the sub-micron level. In an effort to improve the conductor's ability to operate at elevated temperatures, the deformation-processed wires were heat-treated at 260°C to transform the Ca-reinforcing filaments to Al₂Ca. Such a transformation raised the tensile strength by as much as 28%, and caused little change in ductility, while the electrical conductivity was reduced by only 1% to 3%. Al/Al₂Ca composites are compared to existing conductor materials to show how implementation could affect installation and performance.

1. Introduction

A 48% increase in worldwide energy demand is expected by 2040, which will require significant expansion of the electrical power transmission infrastructure [1]. 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 [2]. Conventional aluminum-conductor steel-reinforced (ACSR) cables are not well suited for HVDC transmission due to the presence of the heavy and poorly conducting steel core needed for strength and sag-resistance. Al/Ca composite conductors with monolithic construction 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 both 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 (ROM) prediction [3]. 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 that deforms into sub-micron-thickness filaments during wire drawing, resulting in interface strengthening. Both Al and Ca are ductile fcc metals with high conductivities, similar mechanical properties, and low densities.



One key finding from previous study of Al/Ca composites was the identification of a transformation of the reinforcing Ca phase to the Al₂Ca intermetallic phase at temperatures as low as 175°C, a temperature sometimes reached by transmission conductors during periods of heavy electrical demand [4, 5]. 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 Al/Ca composite 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. % Al₂Ca, found in previous research to be a desirable DMMC reinforcement fraction [6]. The microstructure, temperature stability, conductivity, and mechanical properties were investigated for both Al/Ca and Al/Al₂Ca composite samples.

2. Experimental Procedure

An Al/Ca conductor sample was prepared starting from metal powders produced at Ames Laboratory. Al powder with 99.99% purity of particle sizes 45-75 μm and 99.5% pure Ca with particle size 75-125 μm were used in this study. Powders were weighed (155.45 g Al, 11.45 g Ca, which is 11.5vol.% Ca), blended with a multi-axis mixer (Turbula), and die compacted at a pressure of 61.2 MPa into cylindrical compacts (diameter = 72.1 mm). Each compact had a relative density of 83.8% of the theoretical value (from ROM calculation), in close agreement with the expected room temperature compressibility of Al powder [7]. The compacted powder “pucks” were stacked inside a pure Al (1100-H14 alloy) can with outer diameter 90.7 mm, inner diameter of 78 mm, and interior height of 196.8 mm. Indirect extrusion was performed at the TU Berlin Extrusion Research and Development Center at 285 °C, with an exit die diameter of 21 mm, giving an effective extrusion ratio of 14.9 when accounting for porosity and void space present in the billet. A rod of length 275 cm was sectioned into quarters, and the can material was machined from the rod’s exterior with a lathe. The resulting diameter was reduced at room temperature by swaging to 0.69 mm, at which point wire drawing was used to further reduce the diameter in a series of steps to 0.11 mm. The excellent ductility of the components in the composite allowed all deformation processing to be performed without any stress-relief annealing. The properties investigated in this study were compared on the basis of deformation true strain, as shown in table 1. This is calculated according to equation (1), where d_i and d_f are the initial and final wire diameters, respectively, and η is true strain.

$$\eta = 2 \ln \frac{d_i}{d_o} \quad (1)$$

Table 1: Wire sizes and strain levels for study of 11.5 vol. % Al/Ca.

Diameter (mm)	2.97	2.16	0.94	0.50	0.40	0.31	0.20	0.11
η	6.11	6.74	8.41	9.67	10.1	10.6	11.5	12.7

The microstructure of the wire samples was studied using a FEI Teneo LoVac field-emission scanning electron microscope (FE-SEM). The electrical conductivity was determined by four-point probe measurements at room temperature following ASTM B193-16 [8] by applying a series of currents with a Keithley 6220 Precision Current Source and measuring the voltage difference with a Keithley 2182A nano-voltmeter. Tensile testing was done with multiple instruments to accommodate the various wire sizes that were examined. Larger samples ($\eta < 7$) were tested using an Instron 3367 instrument at an elongation rate of 2 mm/min. For samples with $8 < \eta < 12$, the tensile strength was measured using a Zwick/Roell Z 2.5 instrument at the same elongation rate. For the 0.11 mm diameter ($\eta = 12.7$) wire, tests were completed at Psylotech’s facility using their μ TS (under-microscope) universal test system, allowing for precision measurements at low forces. The ultimate tensile strength (UTS) was used to characterize the samples as it is more reproducible and reliable than yield strength for small specimens and is the strength value most often cited for transmission conductor materials [9].

3. Results and Discussion

3.1 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 [3, 6, 10] and in recent years for the Al/Ca composite system [4, 5, 11]. Figure 1 shows that the ribbon-shaped morphology seen in the prior generation of Al/Ca composites exists at lower strain levels, but is altered by extensive mechanical working. The resultant morphology is in contrast to the expectations of classic composite morphology theory, which predicts cylindrical filaments due to axi-symmetrical deformation of a fcc secondary phase in a fcc matrix. A possible explanation is a temporary crystal structure transformation in the Ca from fcc to bcc during extrusion leading to plane-strain deformation giving rise to a ribbon-like shape [4, 5, 6], but this has not been further explored in this study.

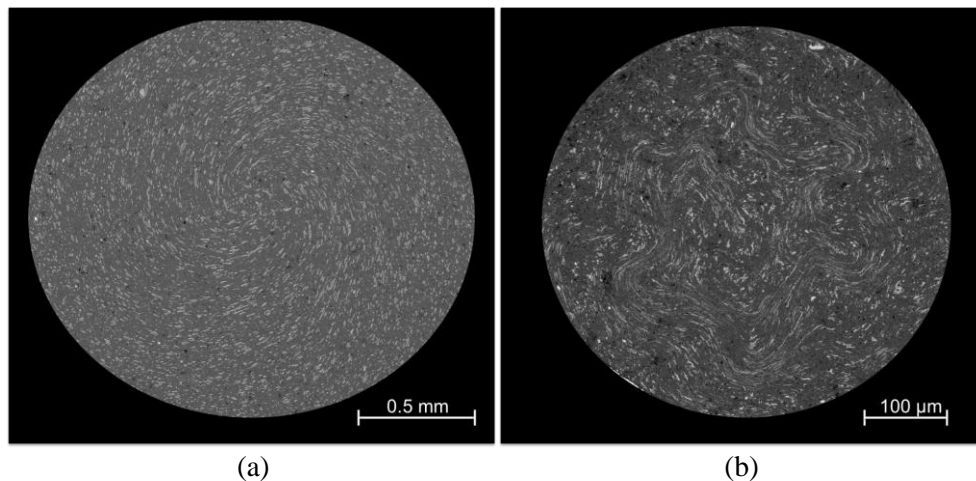


Figure 1. Backscattered electron micrographs of Al/Ca (11.5 vol.%) composite transverse cross section with pure Ca filaments: (a) $\eta=6.74$, (b) $\eta=9.67$.

Following the conversion of the Ca reinforcement to Al₂Ca, the filament size increases, as shown in figure 2. One critical concern with the heat treatment process is spheroidization, which can lead to the breaking of filaments and consequently degradation in mechanical and electrical properties. Based on micrographs at various strain levels, it appears that this did not occur, and the filaments were intact.

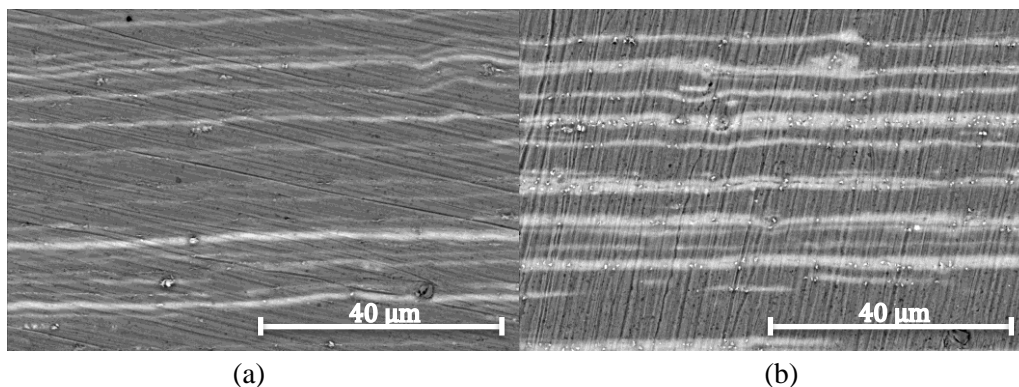


Figure 2. Backscattered electron micrographs of Al/Ca (11.5 vol.%) composite (longitudinal cross section) at $\eta=9.67$: (a) pure Ca filaments, (b) Al₂Ca reinforcement after heat treatment.

The micrographs in figure 2 clearly show a change in the filament size, with a measured increase in thickness from 0.9 μm to 1.5 μm for the selected strain level. This difference is very close to that

expected, indicating that the transformation to Al_2Ca is complete, as was also confirmed by separate differential scanning calorimetry (DSC) and X-ray diffraction studies [4, 5]. The filaments are able to deform with a consistent thickness as Al and Ca have nearly equal flow stresses, avoiding problems with a softer phase flowing around a harder second phase [6, 12]. The filament size 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. DSC experiments and SEM observations confirmed that the transformation was complete but not excessive, enabling development of a heat treatment process and the study of modified performance properties.

3.2 Electrical Conductivity of Al/Ca (11.5 vol.%) and Al/ Al_2Ca (18 vol.%) composites

Given the intended application of Al/Ca composites, conductivity is a critical property in evaluating the commercial viability of this material. The primary advantage of Al/Ca composites is the absence of a highly resistive steel core, needed for strength in conventional conductors (ACSR cables). The monolithic construction allows for high conductivity across the entire cross section with the direction of current flow being parallel to the filaments. Figure 3 shows results of conductivity measurements on both unconverted wires and those that have been transformed at various strain levels.

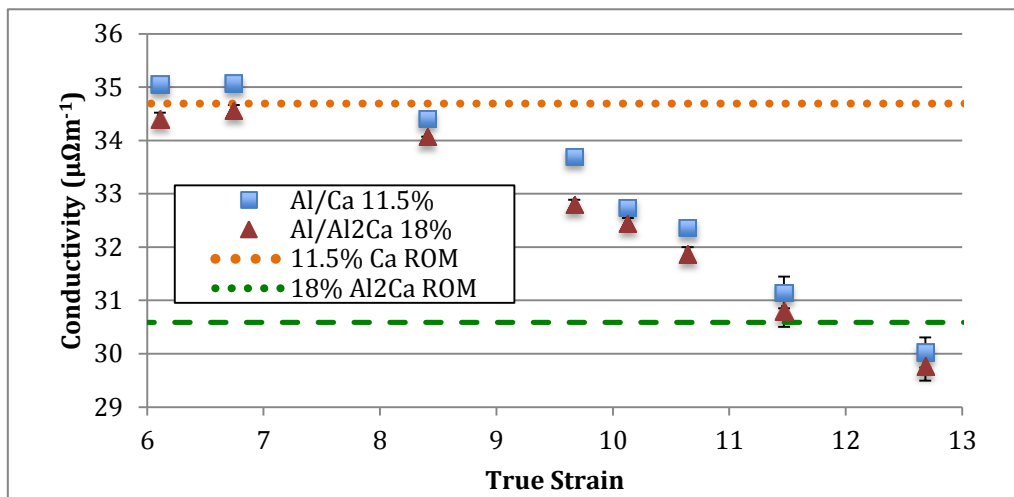


Figure 3. Electrical conductivity of Al/Ca (11.5% vol.) composite before and after transformation of filaments to Al_2Ca intermetallic at various strain levels.

At low strain levels the conductivity is very close to the rule of mixtures prediction for the given formulation, as current flows across the entire cross section and the filament size is significantly larger than the mean free path of the 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 [13].

The effect on conductivity of the transformation of the filaments to Al_2Ca is evident but 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%. With a low loading of Ca in Al/Ca (11.5% vol.), the transformation has a minimal impact (maybe a slight increase) on interfacial area, and, therefore, the influence of interface scattering is not significantly affected. Thus, the very slight reduction observed does not agree with (and is well above) the ROM expectation for Al/ Al_2Ca (18 vol.%), and is a pleasant surprise. Another factor that could cause a decrease in conductivity is a reduced volume fraction of the (highly conductive) Al matrix phase after Ca transformation to Al_2Ca , which has been found to leave the wire diameter essentially unchanged. However, the measured decrease also seems to be less than this effect would indicate, still leaving this beneficial observation unexplained. Therefore, the minimal decrease in conductivity seems to be a worthwhile sacrifice in exchange for the gain in strength and high-temperature stability that the intermetallic phase should provide. With

complete transformation to Al_2Ca , the composite material is expected to have a significantly increased upper operating temperature limit, making it resilient during emergency overloading situations [9].

3.3 Tensile strength of Al/Ca (11.5 vol.%) and Al/ Al_2Ca (18 vol.%) composites

While decreasing the filament size by mechanical working lowers the conductivity of the composite, the primary motivation for doing so is to benefit from the unique strengthening mechanism of DMMCs. 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 greatly exceeding rule of mixture predictions [3]. The stress-strain relationship and fracture surfaces from tensile testing indicated that the composites of the present study still demonstrate ductile behavior upon conversion to intermetallic reinforcement while the ultimate tensile strength increases. Figure 4 shows the exponential relationship between deformation true strain and UTS for as-drawn and converted wire samples at various strain levels, with strength values for commercial cables included for comparison.

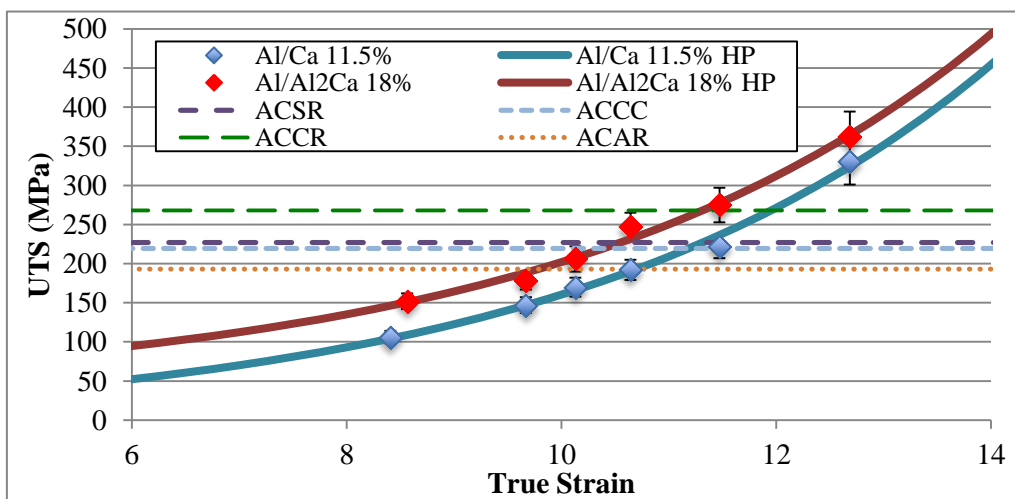


Figure 4. Tensile strength of Al/Ca (11.5% vol.) and Al/ Al_2Ca (18% vol.) composites.

The influence of filament size and fractional loading suggests that interfacial area plays a major role in strengthening the composite. Study of early DMMCs has shown that interphase boundaries act as barriers to dislocation glide leading to interface strengthening [3]. This effect causes the strength to increase sharply at high strains, which has been successfully modeled by a modified Hall-Petch barrier model for the previous generations of Al/Ca composites [4, 5, 11]. Based on measurements of filament thickness (t), the dependence on true strain (η) was assumed to be ideal following the relationship of equation (2) where d_o is the starting Ca filament size.

$$t = d_o e^{-\frac{1}{2}\eta} \quad (2)$$

Using the calculated thickness from equation (2) and the UTS measurements, Hall-Petch relationships were determined for both as-drawn and transformed wires as shown by equations (3) and (4), respectively.

$$UTS = -10.7 + 148 t^{-0.5} \quad (3)$$

$$UTS = 32.3 + 147 t^{-0.5} \quad (4)$$

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 [4, 14, 15]. When compared to Al/Ca (11.5% vol.) it appears that the filament composition (Al_2Ca rather than Ca) has little effect, and that the volume of reinforcement is the dominant factor. The curves for these wires have a very similar shape and differ by an offset for all 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. To account for this the filament thickness calculated by equation (2) needs to be adjusted by a factor related to the volume expansion of the filaments, therefore reducing the effective true strain, which shifts the measured strength values to the left. The major takeaway from analyzing the tensile strength with this adjustment is that Al_2Ca is a more effective reinforcement material than pure Ca and would result in stronger wires at any given volume fraction of reinforcement.

Further study of the material properties of the Al_2Ca compound is necessary in order to utilize more advanced modeling techniques that incorporate the individual contributions from each phase to predict the strength [16]. 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 trade-off between strength and conductivity. In addition to these considerations, the highest attainable strain level seems to be dictated mainly by the starting billet size and the ram force of the commercial extrusion capabilities that are available.

3.4 Comparison of Al/ Al_2Ca (18 vol.%) composites to commercial cable technologies

Al/ Al_2Ca composites have potential to be used as electrical conductors in applications with various demands due to the ability to tailor the performance properties of wires used for the construction of a monolithic cable. It has been shown that strength superior to other cable technologies is attainable while not sacrificing a large amount of conductivity. In addition to these properties, the proposed conductor material has a low density allowing for the use of larger conductors. Figure 5 shows a summary of the electrical conductivity and the specific strength (UTS/density) of the wires studied and of commercial wires that would be suitable for HVDC transmission.

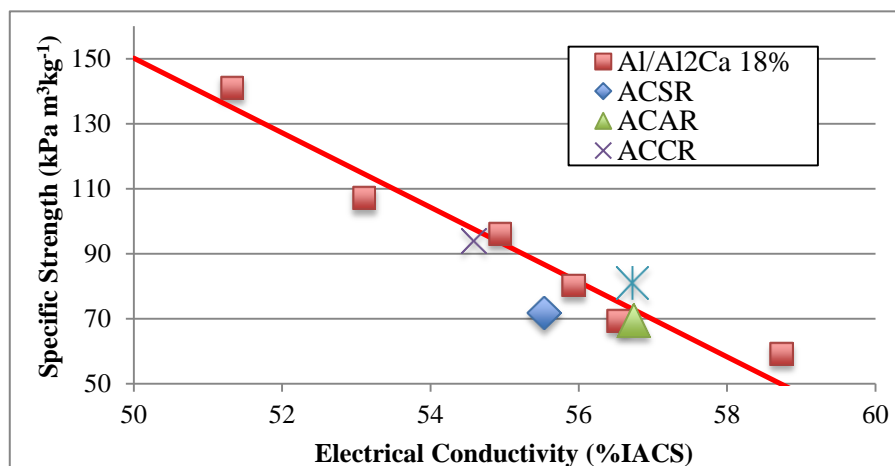


Figure 5. Summary of specific strength and electrical conductivity of Al/ Al_2Ca composites and commercial cable technologies.

Selection of the best balance of strength and conductivity is dependent on whether an existing line is replaced or a new line is being constructed. Figure 5 shows that the conductivity is very similar to commercial wires for a given strength level at lower strain values. Being able to achieve high strength is appealing due to the impact that this can have on increasing the spacing of support towers. To further analyze the trade-offs in selecting a conductor, a 500kV, 3500 MW, 1360 km HVDC line, analogous to the Pacific DC Intertie, was considered [17]. Figure 6 shows the number of towers required and the annual cost of electrical losses (\$0.05/kWh) for each conductor to deliver the same amount of power, given the same conductor sag as for the existing design that is based on ACSR cables.

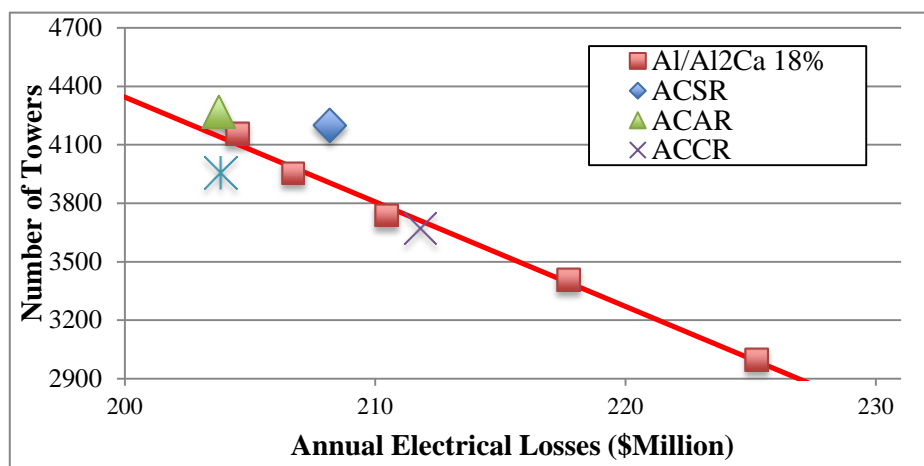


Figure 6. Comparison of initial investment in towers and electrical losses for Al/Al₂Ca composites and commercial cable technologies for 1360 km HVDC line.

Comparing the conductors in this fashion enables a decision on material selection to be made based on economics. Having a high strength can reduce the number of towers required, which has the potential to substantially lower installation costs. For the wires with the greatest strain ($\eta = 12.7$), 29% fewer towers would be needed, and the electrical losses would be 8.2% greater compared to using ACSR cables. Al/Al₂Ca composites could be especially useful as long-span conductors for river or canyon crossings where high strength is required. Moreover, the ability to alter the volume fraction and true strain allows for precise control of material properties, while cable construction is simplified by using a single material.

4. 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 and the mechanical strength and electrical conductivity evaluated. Based on these investigations the following conclusions can be made:

- After controlled transformation of the reinforcement phase, volume expansion occurred producing a Al/Al₂Ca (18vol.%) composite. Longitudinal micrographs revealed no apparent filament instabilities or spheroidization.
- The electrical conductivity of the Al/Ca (11.5% vol.) composite decreased with reduced filament spacing at high true strains, consistent with previous results. The transformation of Ca filaments to Al₂Ca caused the conductivity to drop by less than 1% for wires subjected to the greatest level of deformation in this study ($\eta = 12.7$).
- 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 Ca reinforcement phase to Al_2Ca due to the increase in volume fraction and strength of the reinforcement phase, but retention of ductility was also observed.

- Al/Al_2Ca composite wires show promise to exhibit strength superior to current cable technologies combined with high electrical conductivity, low density, and likely high-temperature performance and stability, making them excellent candidates for use as HVDC transmission conductors.

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