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Enhancing Aluminum Alloys for High-Strength Electrical Conductor with Nanoparticle Reinforcement

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Abstract: This study explores AlZrCe alloy, reinforced with Al_2O_3 nanoparticles, as a potential substitute for Aluminum Conductor Steel Reinforced (ACSR) materials in electric transportation infrastructure, including vehicles, trams, and trains. The Al-0.12%Zr-0.15%Ce master alloy incorporates Al_2O_3 nanoparticles (0-2%). Fabrication involves homogenization and casting. Research assesses the effects of solid solution treatment and cold rolling on microstructure, electrical conductivity, tensile strength, and hardness. Microstructural analysis reveals reduced alumina particle aggregation with increased thickness reduction, improving tensile strength, hardness, and electrical conductivity. This composite offers promise for high-strength conductor materials, supporting energy and material conservation.

Keywords: Al_2O_3 nanoparticles; AlZrCe; Solid solution; Cold rolling; Electrical conductivity

1. Introduction

In contemporary engineering applications, aluminum alloys are increasingly gaining prominence as viable alternatives to traditional materials such as steel and wood. This transition is attributed to the numerous advantages offered by aluminum and its alloys, including commendable corrosion resistance, low specific gravity, and excellent electrical conductivity1,2). Moreover, aluminum alloys exhibit a lower specific gravity, coupled with a more cost-effective price point, making them an attractive choice for various industries3). Notably, the evolution of aluminum alloys extends to their application as electrical conductors in high voltage transmission networks, gradually replacing conventional copper materials4).

To enhance the overall performance of aluminum in diverse applications, concerted efforts are directed towards refining its physical and mechanical properties5,6,7,8). This involves the incorporation of alloying elements into pure aluminum5), accompanied by various mechanical and thermal treatments6,7,8). The introduction of alloying elements results in the formation of a solid solution or precipitates in the form of intermetallic compounds. For instance, the addition of 0.12% Zr element to aluminum leads to the creation of the Al_3Zr intermetallic phase, imparting remarkable heat resistance by resisting recrystallization9,10). This phenomenon elevates the recrystallization temperature of aluminum, thereby optimizing its structural integrity under high-temperature conditions11). It is noteworthy that the recovery and recrystallization phase in aluminum can compromise its strength, as dislocations begin to disintegrate, and the strain strengthening effect diminishes12). However, studies, including those by Ning13), have observed the inhibition of grain boundary growth by Al_3Zr, demonstrating its effectiveness in maintaining the structural integrity of aluminum.

Given the high heat loads experienced by aluminum conductors in high voltage transmission, there is a propensity for reduced tensile strength14). To counteract this, Zr is commonly added to pure aluminum to enhance its thermal resistance. Although the addition of Zr tends to decrease electrical conductivity, this drawback can be mitigated by incorporating rare earth metal elements, such as cerium (Ce). The mechanism underlying the increase in electrical conductivity involves the formation of intermetallic compounds with impurities in aluminum, such as Fe and Si. These intermetallic compounds, including $FeAl_3$ or Ce_5Si_3, precipitate at grain boundaries, reducing impurities within the aluminum crystal grains. Consequently, this minimizes distortion among aluminum atoms, thereby increasing the electron delivery rate15).

This research aligns with findings from various scholars, such as Pan16), Murashkin17), Zulfia18), and Chaubey19), who have reported similar outcomes in their studies, albeit with varying Ce content values. The collective body of research underscores the promising potential of aluminum alloys in achieving a balance between mechanical strength, thermal resistance, and electrical conductivity for diverse applications, particularly in high voltage transmission networks.

In the pursuit of enhancing the strength of aluminum alloys, one avenue of exploration involves the creation of metal matrix composites (MMC). These composites are formed by incorporating reinforcing fibers or particles, such as Al_2O_3 (alumina) and SiC, into the aluminum matrix. The fabrication of MMC with ceramic particle reinforcement is commonly achieved through techniques like stir casting or powder metallurgy[20, 21, 22]. The most important step in this procedure is stirring[23, 24, 25]. The stir casting method, as studied by Kirman[26], involves the incorporation of alumina particles into the AlZrCe alloy using a specific combination of alloying elements (0.15% Ce, 0.12% Zr), showcasing its potential in conductor applications. Another study by Zulfia[27] delves into the influence of alumina and magnesium particles in AlZrCe on both electrical and mechanical properties, providing further insights into the multifaceted nature of composite materials.

In addition to the incorporation of reinforcing particles, the mechanical properties of aluminum alloys can be enhanced through plastic deformation processes, including hot rolling, cold rolling, extrusion, and wire drawing[28]. These processes contribute to the refinement of the alloy's microstructure, thereby improving its overall mechanical strength. The conventional manufacturing process for conductor wires involves sequential stages of continuous casting, hot rolling, and wire drawing, demonstrating a comprehensive approach to producing conductive materials with tailored mechanical characteristics.

The specific focus of the current research is to investigate the alterations in mechanical properties and electrical conductivity of composite rods derived from the AlZrCe alloy reinforced with alumina particles. This investigation employs the solid solution process followed by cold rolling, aiming to optimize the composite's performance for potential applications in various engineering domains. By systematically exploring the interplay between alloy composition, reinforcement particles, and processing techniques, this research endeavors to contribute valuable insights towards the development of high-performance aluminum-based composites with enhanced mechanical and electrical properties.

2. Experimental Method

The experimental material under investigation comprises an AlZrCe alloy composite rod, wherein alumina particles serve as the reinforcing agents, thereby constituting a metal matrix composite (MMC). The compositional details of the AlZrCe alloy, functioning as the composite matrix material, are delineated in Table 1. The synthesis of the AlZrCe/Al_2O_3np nanocomposite was achieved through the stir casting method, wherein the concentration of Al_2O_3np reinforcement was systematically varied within the range of 0 to 1.2 V_f%. The intricate casting process initiated with the incorporation of reinforcement into the matrix through a meticulous procedure involving the envelopment of particles in aluminum foil, subsequent insertion into aluminum foil capsules, and eventual immersion into the molten aluminum alloy within the furnace. The molten aluminum underwent a refinement process, involving degassing with inert argon gas and stirring at a rotational speed of 500 rpm, maintaining a temperature of 750°C for a duration of 2 to 3 minutes. The introduction of nano-sized Al_2O_3 particles into the molten Al alloy induced a marked increase in viscosity. Subsequently, the molten metal matrix composite was precisely cast into a permanent tensile test mold, left to undergo controlled cooling and solidification, thereby resulting in the formation of an as-cast sample.

The cold rolling process applied to the AlZrCe/Al_2O_3np composite involves sequential reductions in thickness, transitioning from an initial thickness of 9 mm to 6 mm (a 33% reduction), further down to 4 mm (a 56% reduction), and ultimately to 2 mm (a 78% reduction). The cold-rolled specimens encompass both untreated as-cast samples and those subjected to a solid-solution heating treatment. The latter involves exposing the samples to a temperature of 500°C for a duration of 1 hour, followed by a controlled cooling process to return them to room temperature. This solid-solution heating treatment aims to optimize the solubility of alloy elements within the matrix. Figure 1 illustrates the employed rolling machine and the resulting samples subsequent to the cold rolling procedure, providing a visual representation of the structural transformations incurred during this critical phase of material processing. This systematic approach facilitates a comprehensive exploration of the mechanical and microstructural alterations induced by the cold rolling process, contributing valuable insights into the performance and characteristics of the AlZrCe/Al_2O_3np composite.

Table 1. Chemical composition of Al-Zr-Ce alloy

Alloy material	Weight %					
	Al	Zr	Ce	Si	Fe	others
Al-Zr-Ce	98.30	0.12	0.15	0.39	0.88	0.16

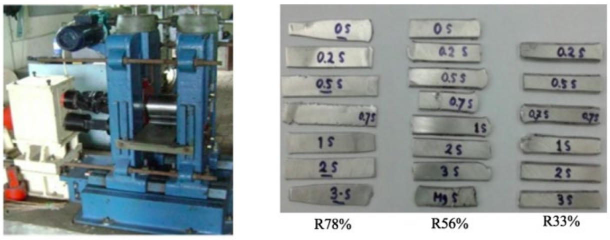


Fig. 1: (a) Two high mill type rolling machine for cold rolling process, rolling diameter 140 mm and (b) cold rolling samples with thickness reduction of 33%, 56% and 78%

The microstructural characterization of the AlZrCe/Al_2O_3np composite was conducted through optical microscopy and Field Emission-SEM (FE-SEM) employing the Inspect F50 model. Metallographic samples, obtained from both as-cast and cold-rolled materials aligned with the rolling direction, underwent meticulous preparation following standard procedures[29)]. Subsequently, these samples were etched in a Keller reagent solution comprising 50 ml aqudes, 50 ml HNO_3, 10 ml HCl, and 10 ml HF. The distribution of alloy constituents was further investigated utilizing the energy dispersive spectrometer (EDS) system integrated with the SEM. Mechanical properties were probed through hardness tests and tensile tests. The former involved applying a 1.5 N load for 5 seconds at three different points within each metallographic sample. Tensile properties were assessed using a universal testing machine at a speed of 5 mm/s, with measurements conducted on a gauge length of 12 mm and a width of 5 mm for each sample. Additionally, the electrical conductivity of the samples was determined employing the eddy current method, with comparisons drawn against annealed copper (100% IACS). This comprehensive analytical approach provides a detailed understanding of both the microstructural and mechanical attributes of the AlZrCe/Al_2O_3np composite, offering valuable insights for further advancements and applications in materials science.

3. Results and Discussions

3.1 Microstructure of AlZrCe/Al2O3np

In this study, the microstructural evolution of the AlZrCe/Al_2O_3np composite subjected to cold rolling was systematically investigated. The casting process yielded two distinct sample conditions: the as-cast sample and the solid solution sample, the latter being subjected to a thermal treatment at 500°C for 1 hour. Cold rolling was subsequently implemented with thickness reduction percentages of 33%, 56%, and 78%. The effects of this process on the microstructure were profound, notably mitigating porosity and transforming particle agglomerates from a round to an elongated flat shape in the rolling direction, as depicted in Fig. 2.

The microstructure of the as-cast composite exhibited a dendritic pattern, with some grains appearing elongated and unidirectional, while others remained equiaxed. This morphology is typical of gravity-cast metals[30, 31)]. Dark regions at the grain boundaries indicated the presence of alumina particles and intermetallic compounds combined with cerium. Figures 2(b), (c), and (d) illustrate the microstructure of the cold-rolled composite at thickness reduction percentages of 33%, 56%, and 78%. The microstructure became thinner and manifested as elongated lines in the rolling direction. Notably, alumina particles, previously agglomerated, exhibited a more uniform distribution along the grain boundaries, particularly with an increase in the percentage of rolling reduction.

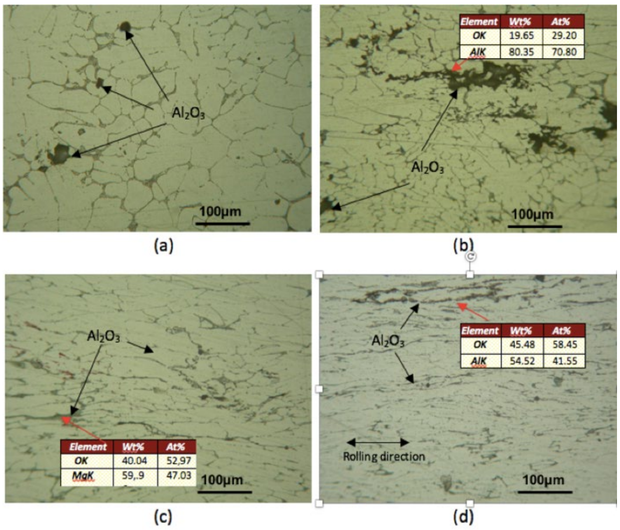


Fig. 2: Microstructure forms with various rolling reduction percentages (a) as-cast, (b) 33% reduction, (c) 56% reduction and (d) 78% reduction

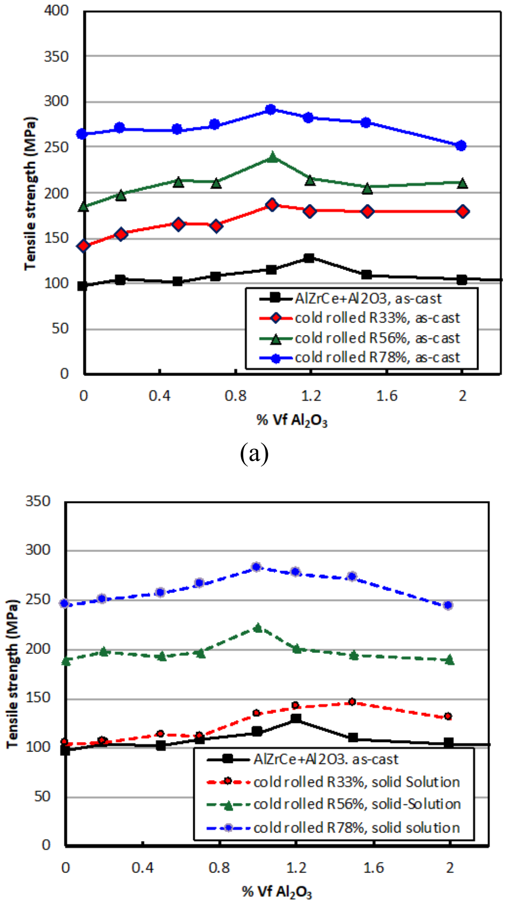
The cold rolling process induced a dispersion of grain particles across the grain boundaries, with firm embedding observed. This phenomenon serves as a manifestation of the Orowan strengthening mechanism[32, 33)]. The tensile strength of the composite increased due to the impediment posed by alumina particles functioning as locking pegs, resisting dislocation movement between grains. Tensile strength augmentation correlated positively with increasing reduction percentages, as the greater the reduction, the more elongated the shape of porosity and particle agglomerates in the rolling direction, as illustrated in Fig. 2. This detailed microstructural analysis elucidates the intricate mechanisms underlying the improvement in mechanical properties, offering valuable insights for optimizing the cold rolling process for enhanced composite performance.

3.2 Tensile strength, hardness, and electrical properties of AlZrCe/Al_2O_3np nanocomposite.

The tensile strength, hardness, and electrical properties of the AlZrCe/Al_2O_3np nanocomposite were systematically investigated, with a focus on both as-cast and solid-solution conditions. Figure 3 illustrates the results of the tensile tests conducted on specimens from both conditions. Notably, a consistent trend of increasing tensile strength with respect to alumina volume fraction content was observed post-rolling. Furthermore, a particular correlation emerged between the tensile strength levels and the percentage of rolling reduction.

In the absence of the rolling process, the baseline tensile strength rested at approximately 100 MPa. Following the cold rolling procedure, a remarkable augmentation in tensile strength was evident, with levels approaching 300

MPa observed for specimens subjected to a substantial 78% thickness reduction. This compelling enhancement in tensile strength underscores the profound influence of the cold rolling process on the mechanical characteristics of the nanocomposite. The findings highlight the potential for tailoring the mechanical properties of the AlZrCe/Al_2O_3np nanocomposite through judicious control of both alumina volume fraction and the extent of rolling reduction, offering valuable insights for optimizing the composite's performance in practical applications.

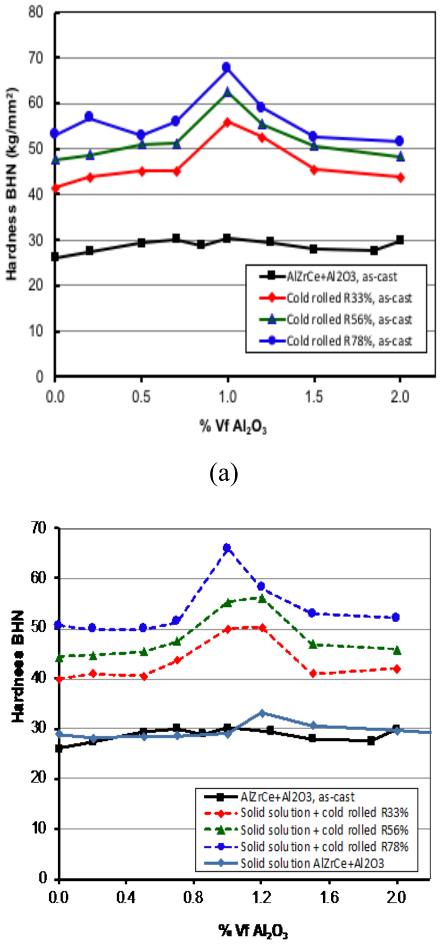


(a)

(b)

Fig. 3: Tensile strength of Al-Zr-Ce/Al2O3 nanoparticle composite after cold rolling process, (a) as-cast (b) solid-solution temperature 500°C for 1 hour.

In examining the mechanical attributes of the AlZrCe/Al_2O_3np nanocomposite, the hardness test results for both as-cast and solid-solution conditions are depicted in Fig. 4. A noteworthy parallelism was observed between the trends in hardness values and those in tensile strength after the cold rolling process. Specifically, an increase in the percentage of rolling reduction correlated with a substantial enhancement in hardness. In the absence of cold rolling, the baseline hardness level for the composite was around 30HB. However, post-rolling reductions of 33%, 56%, and 78% resulted in a pronounced surge in hardness, exceeding 40HB for both the as-cast and solid-solution composite conditions. The increase in mechanical properties as a result of cold rolling was also reported by other researchers[34].



(a)

(b)

Fig. 4: Hardness of AlZrCe/Al_2O_3 nanoparticle composite after cold rolling process, (a) as-cast condition (b) solid solution condition at temperature 500°C, 1 hour

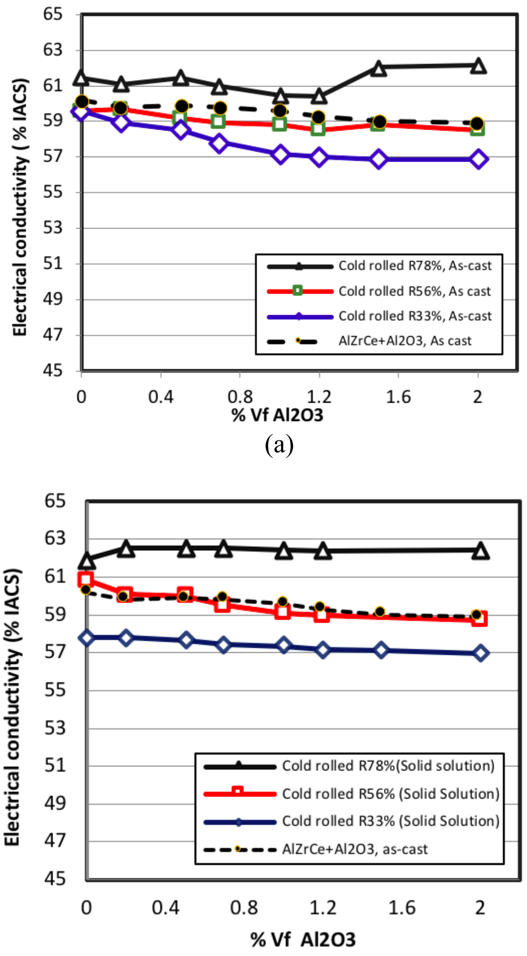
An interesting observation emerged from the hardness test results, revealing that the influence of reinforcing particle content in the composite became more pronounced after cold rolling. Unlike the stability of hardness values without cold rolling concerning changes in the volume fraction content of Al_2O_3 reinforcing particles, the post-cold rolling hardness exhibited significant variations with alterations in particle volume fraction content. This notable effect stems from the enhanced dispersion and compression of reinforcing particles at the grain boundaries, thereby augmenting the overall hardness of the material. This stands in stark contrast to as-cast composites without rolling, where reinforcing particles tended to form agglomerates and clusters, weakening the material due to a lack of robust binding to the grain boundaries.

The maximum hardness value for the as-cast sample was consistently observed at 1%V_f for each rolling reduction percentage. In contrast, for the solid-solution sample, the maximum hardness value was observed at both 1%V_f and 1.2%V_f. Following cold rolling, the maximum hardness value surged beyond 65 HB, representing an increase exceeding 100%. This pronounced enhancement is attributed to the scattering of particles at the grain boundaries, firmly embedding them in the grain boundaries post-rolling, thereby acting as effective locking pins to resist dislocation movement between grains. The observed increase in hardness correlates positively with increasing reduction percentages, underscoring the pivotal role played by the cold rolling process in refining the matrix grains, porosity, and particle agglomerates, as elucidated in Fig. 2. These findings contribute valuable insights for tailoring the mechanical properties of the nanocomposite for diverse applications.

The examination of electrical conductivity in the AlZrCe/Al_2O_3np nanocomposite post-cold rolling revealed a marked enhancement in both as-cast and solid solution conditions, as illustrated in Fig. 5. The percentage effect of cold rolling reduction exhibited a nuanced trend for as-cast samples and solid solution conditions. A reduction of 33% initially resulted in decreased electrical conductivity, followed by a subsequent increase at a reduction of 56%, reaching a value approximately equivalent to pre-cold rolling levels. Strikingly, the electrical conductivity continued to rise with a reduction of 78%, surpassing the conductivity of the as-cast matrix material.

A reduction of 33% in electrical conductivity has been observed in comparison to the as-cast state. This finding arises from thorough test measurements conducted on seven specimens featuring varying volume fractions of Alumina. The lower electrical conductivity of specimens is most likely a result of the overall reduction in the area available for electrical flow by 33%, impacting the aluminum metal component most significantly. Despite the reduced area, Alumina clusters persist in a dispersed and coarse form, displaying resistance to electrical current, as depicted in Fig. 2b. This dynamic interplay between the altered cross-sectional area and the resilient, scattered Alumina clusters provides valuable insights into the nuanced effects on the electrical conductivity of the samples.

Remarkably, the electrical conductivity of the solid solution composite after cold rolling with a reduction of 78% reached a level of 62.5% IACS, almost comparable to the electrical conductivity of pure aluminum (64% IACS). This notable increase in electrical conductivity post-cold rolling can be attributed to the arrangement of non-conductive Al_2O_3 particles at the grain boundaries, aligned parallel to the direction of electric flow. Additionally, impurity elements such as Si and Fe, bound to Ce in the intermetallic phase, are also situated at the grain boundaries where the thin matrix grains extend in the direction of the electric current, namely in the rolling direction.



(a)

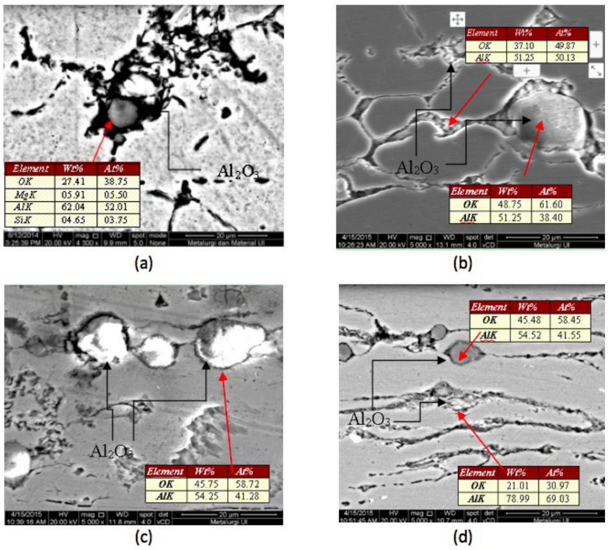
(b)

Fig. 5: Electrical conductivity of Al-Zr-Ce/Al_2O_3 nanoparticle composite after cold rolling process, (a) as-cast and (b) solid solution 500°C, 1 hour.

Furthermore, the solid-solution composite exhibited a more substantial increase in electrical conductivity. The elevated temperature treatment at 500°C for 1 hour is anticipated to induce maximum dissolution of solid Ce elements, facilitating the optimal migration of Fe and Si impurity elements to the grain boundaries to form an intermetallic phase. This intricate interplay of factors elucidates the substantial enhancement in electrical conductivity observed in the nanocomposite, underscoring the potential for tailoring its electrical properties through careful control of processing conditions.

3.3. Interface area between matrix and reinforcement

The SEM observations in Fig. 6 provide a comprehensive view of the AlZrCe/Al_2O_3np composite following the cold rolling process, comparing the unrolled composite with thickness reductions of 33%, 56%, and 78%. The investigation reveals a noteworthy reduction in the influence of clusters or agglomerations of alumina particles after rolling. Cold rolling transforms agglomerated particles into elongated structures aligned with the rolling direction, consequently enhancing their mechanical strength. The direct correlation between the percentage of cold rolling reduction and the resultant increase in tensile strength and hardness values is evident, underscoring the effectiveness of the cold rolling process in refining the composite's microstructure.



Element	Wt%	At%
OK	27.41	38.75
MgK	05.91	05.50
AlK	62.04	52.01
SiK	04.65	03.75

Element	Wt%	At%
OK	37.10	49.87
AlK	51.25	50.13

Element	Wt%	At%
OK	48.75	61.60
AlK	51.25	38.40

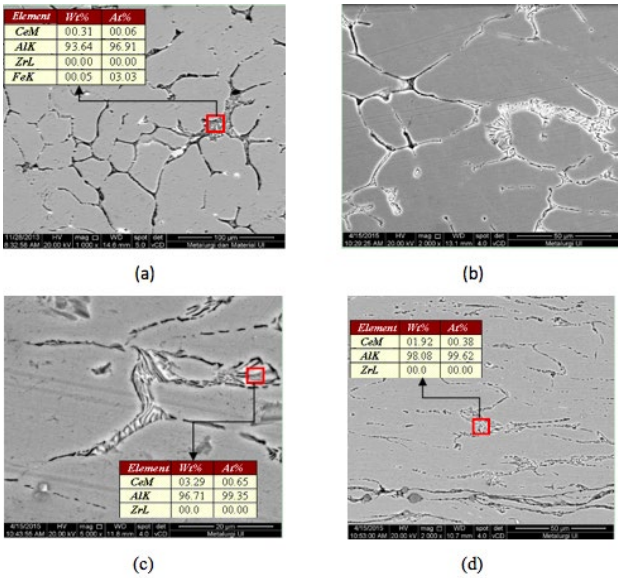
Element	Wt%	At%
OK	45.75	58.72
AlK	54.25	41.28

Element	Wt%	At%
OK	45.48	58.45
AlK	54.52	41.55

Element	Wt%	At%
OK	21.01	30.97
AlK	78.99	69.03

Fig. 6: Al_2O_3 nanoparticles in the AlZrCe/Al_2O_3 composite show Al_2O_3 particles and agglomerates of Al_2O_3 particles located at the grain boundaries; (a) as-cast composite (b) 33% reduction, (c) 56% reduction and (d) 78% reduction

Furthermore, SEM-EDS test results depicted in Fig. 6 highlight the presence of cerium, alumina, and other metals such as magnesium and iron at the grain boundaries. This observation aligns with previous studies indicating the formation of intermetallic compounds at grain boundaries$^{35)}$. Rare earth (RE) metals like cerium and lanthanum typically form precipitates at grain boundaries rather than dissolving in aluminum, as corroborated by other research$^{36)}$. While zirconium exhibits a solubility of up to 0.23% in aluminum, the addition of cerium reduces solubility, resulting in the formation of Al_3Zr compounds that persist at the grain boundaries. Meanwhile, a limited number of alumina particles consistently reside at the grain boundaries.



Element	Wt%	At%
CeM	00.31	00.06
AlK	93.64	96.91
ZrL	00.00	00.00
FeK	00.05	03.03

Element	Wt%	At%
CeM	03.29	00.65
AlK	96.71	99.35
ZrL	00.0	00.00

Element	Wt%	At%
CeM	01.92	00.38
AlK	98.08	99.62
ZrL	00.0	00.00

Fig.7: The intermetallic phase consisting of Ce elements at the grain boundaries whose shape decreases as the reduction percentage increases (a) as-cast composite (b) 33% reduction, (c) 56% reduction and (d) 78% reduction

The electrical conductivity properties exhibit an upward trend with an increasing reduction percentage in cold rolling. This phenomenon is attributed to the diminished size of particle clusters and the elongation of matrix grains in the rolling direction, minimizing the hindrance posed by impurity elements such as silicon and iron at the grain boundaries to the electric current flow. The nanoscale alumina particles act as pins or pegs at the grain boundaries, impeding the movement of dislocations and rendering grain boundary dislocation more challenging. This effect is visually corroborated by the presence of alumina grains at the grain boundaries, as depicted in Fig. 6. Additionally, the phases formed due to zirconium and cerium additions appear smaller and elongated in Fig. 7, reducing resistance to electrical flow. Hence, a direct relationship between the reduction percentage and enhanced electrical conductivity values is established, affirming the role of cold rolling in tailoring the electrical properties of the composite.

4. Conclusion

The application of the cold rolling process to the AlZrCe/Al_2O_3np composite induces significant modifications in grain shape, orientation, porosity, and particle agglomeration, leading to notable improvements in its mechanical and electrical properties. A direct relationship was observed between the percentage of thickness reduction in cold rolling and enhanced tensile strength, hardness, and electrical conductivity.

Cold rolling with a 78% reduction demonstrated remarkable improvements in mechanical properties, elevating tensile strength to nearly 300 MPa and hardness to approximately 70 HB. Additionally, the combined approach of solid-solution heat treatment followed by cold rolling with a 78% reduction resulted in a noteworthy increase in electrical conductivity, reaching 62.5% IACS, a value close to the electrical conductivity of pure aluminum (EC 99.6%) at 63.4% IACS.

The composite, specifically the AlZrCe/1%Vf.Al_2O_3, subjected to solid-solution heat treatment and a cold rolling process with a 78% reduction, exhibited superior tensile and electrical properties, recording values of 282 MPa and 62.4% IACS, respectively. This remarkable performance surpasses conventional electrical conductor cables employed in electricity transmission applications. The findings underscore the efficacy of the proposed processing approach in tailoring the AlZrCe/Al_2O_3np composite for advanced applications, particularly in contexts where superior mechanical strength and electrical conductivity are paramount.

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