A Review of Sustainable High-Performance Materials: Hybrid AA 7068/ZRO_2/Fly Ash Composites for Advanced Engineering Applications

M B Niyaz Ahamed[1]*, Dr. Madhusudhan M[2], Vikram Kedambadi Vasu[3]

[1]Research Scholar, Department of Mechanical Engineering, Presidency School of Engineering, Bengaluru, Karnataka, Email: niyaz.budensab@utas.edu.om
[2]Assistant Professor and Assistant Controller of Examinations, Department of Mechanical Engineering, Presidency School of Engineering, Bengaluru, Karnataka, Email: madhusudhan@presidencyuniversity.in
[3]Assistant Professor, Department of Mechanical Engineering, Nitte Meenakshi Institute of Technology, Bengaluru, Karnataka, Email: vikramkv123@gmail.com

***Corresponding Author:** M B Niyaz Ahamed
*Email: niyaz.budensab@utas.edu.om

Abstract
Hybrid metal matrix composites (HMMCs) have emerged as a promising class of materials, offering superior mechanical, thermal, and tribological properties for advanced engineering applications. This study explores the potential of developing AA 7068-based hybrid composites reinforced with zirconium dioxide (ZrO_2) and fly ash, aiming to enhance strength, wear resistance, and sustainability. AA 7068, a high-strength aluminum alloy, is identified as a suitable matrix material due to its exceptional mechanical properties and corrosion resistance. ZrO_2, a ceramic reinforcement with high hardness and fracture toughness, is expected to improve wear resistance and mechanical strength. Fly ash, an industrial byproduct, offers the benefits of weight reduction, damping enhancement, and environmental sustainability. A comprehensive literature survey indicates that the combination of AA 7068 with ZrO_2 and fly ash has the potential to yield a lightweight, high-strength composite with improved thermal stability and wear resistance. Based on prior research, stir casting is considered a viable fabrication method for achieving uniform reinforcement distribution and cost-effective production. Future experimental investigations will focus on fabricating and characterizing these hybrid composites to evaluate their mechanical, tribological, and thermal properties. The anticipated results could pave the way for their application in aerospace, automotive, and structural industries, where lightweight and high-performance materials are crucial. Further research will aim to optimize processing conditions, reinforcement dispersion, and interfacial bonding to maximize the material's performance and industrial viability.

Keywords: Hybrid Composites, AA 7068, Zirconia (ZrO_2), Fly Ash, High-Performance Materials

1. Introduction

Hybrid composites have emerged as a promising class of materials that combine multiple reinforcing phases within a metal matrix, leading to enhanced mechanical, thermal, and tribological properties. The selection of suitable reinforcement materials is crucial in tailoring the performance of hybrid composites for industrial applications [1]. Among various metal matrix composites (MMCs), aluminum-based composites are widely explored due to their excellent strength-to-weight ratio, corrosion resistance, and manufacturability. AA 7068, a high-strength aluminum alloy, has been identified as an ideal matrix material for hybrid composites due to its superior mechanical strength, toughness, and wear resistance. It is one of the strongest aluminum alloys, primarily used in aerospace, defense, and high-performance structural applications. However, the mechanical properties of AA 7068 can be further enhanced by incorporating reinforcements such as zirconium dioxide (ZrO_2) and fly ash [2]. Zirconia (ZrO_2) is a ceramic material known for its excellent wear resistance, thermal stability, and high fracture toughness. The addition of ZrO_2 as a reinforcement in the aluminum matrix improves hardness, thermal resistance, and strength while maintaining the material's ductility to some extent. ZrO_2 has also been shown to enhance the toughness of brittle materials by undergoing phase transformation toughening, which plays a significant role in improving the composite's performance under mechanical loading. Fly ash, an industrial byproduct generated from coal combustion in power plants, has gained attention as a cost-effective reinforcement material. It primarily consists of alumina (Al_2O_3), silica (SiO_2), and iron oxide (Fe_2O_3), making it a potential candidate for lightweight structural composites. Fly ash particles contribute to weight reduction, improved wear resistance, and enhanced damping properties in hybrid composites. Additionally, the incorporation of fly ash in aluminum composites promotes sustainability by recycling industrial waste into high-performance materials [3-4].

The development of AA 7068-ZrO_2-Fly Ash hybrid composites is expected to yield a material with exceptional properties, including:

- Enhanced Strength and Hardness: The reinforcement phases contribute to load transfer efficiency, dislocation strengthening, and grain refinement, leading to superior mechanical properties [5].
- Improved Wear and Corrosion Resistance: ZrO_2 provides excellent wear resistance, while the passive oxide layer on AA 7068 enhances its corrosion resistance [6].
- Weight Reduction: Fly ash, being a low-density material, reduces the overall weight of the composite, making it ideal for aerospace and automotive applications [7].
- Better Thermal Stability: The ceramic reinforcements improve the high-temperature stability and thermal resistance of the composite [8].
- Sustainability and Cost-Effectiveness: The use of fly ash promotes eco-friendly material development by utilizing industrial waste [9].

Despite these advantages, challenges such as interfacial bonding between the matrix and reinforcements, processing difficulties, and the distribution of secondary phases need to be addressed to optimize the performance of these hybrid composites. Advanced manufacturing techniques, including powder metallurgy, stir casting, and additive manufacturing, play a crucial role in fabricating these materials with controlled microstructures. This study comprehensively explores the processing techniques, mechanical properties, applications, and potential challenges associated with AA 7068-ZrO_2-Fly Ash hybrid composites. The findings aim to provide insights into the feasibility of these composites in structural and industrial applications, particularly in sectors such as aerospace, defense, and automotive engineering.

2. Composite Fabrication Methods

The fabrication of hybrid AA 7068/ZrO_2/Fly Ash composites requires advanced manufacturing techniques to ensure uniform dispersion of reinforcements, improved interfacial bonding, and optimal mechanical properties. The choice of manufacturing process significantly influences the composite's microstructure, phase distribution, mechanical strength, and wear resistance. Two widely employed methods for producing these hybrid composites are Powder Metallurgy and Stir Casting.

2.1 Powder Metallurgy

Powder metallurgy (PM) is a widely used technique for producing metal matrix composites (MMCs) with precise control over composition, particle distribution, and porosity. The PM process for AA 7068/ZrO_2/Fly Ash composites involves the following steps:

- Powder Preparation: The raw materials (AA 7068, ZrO_2, and fly ash) are obtained in fine powder form to ensure uniform mixing.
- Blending and Ball Milling: Mechanical alloying via ball milling is used to achieve homogeneous dispersion of the reinforcement particles. High-energy ball milling enhances the interfacial bonding between the matrix and reinforcements.
- Compaction: The p owder mixture is compacted under high pressure using uniaxial or cold isostatic pressing to form a green compact.
- Sintering: The compacted specimen is subjected to high temperature sintering in a controlled atmosphere to promote diffusion bonding and densification. The sintering temperature is optimized to avoid excessive grain growth while maintaining good mechanical properties.
- Post-processing: Secondary treatments such as hot isostatic pressing (HIP) or surface machining may be performed to improve the final properties of the composite.

  Powder metallurgy ensures fine microstructural control, but challenges such as porosity, limited part size, and potential segregation of reinforcement particles must be addressed [10-13].

2.2 Stir Casting

Stir casting is a cost-effective liquid metallurgy technique for fabricating hybrid metal matrix composites as shown in Figure 1. This method involves the incorporation of ceramic and fly ash reinforcements into the molten AA 7068 matrix through mechanical stirring, ensuring a relatively uniform distribution of reinforcements [14-18]. The key steps in stir casting include:

- Matrix Preparation: AA 7068 is melted in a graphite or alumina crucible at a controlled temperature (typically above 700°C). A flux may be added to prevent oxidation.
- Reinforcement Pre-treatment: ZrO_2 and fly ash particles are preheated to remove moisture and surface contaminants, which enhances their wettability with the molten aluminum alloy.
- Stirring and Mixing: A mechanical stirrer (coated with a non-reactive material) is used to introduce the reinforcement particles into the molten matrix. Stirring is performed at a controlled speed (300–600 rpm) for a specific duration (5–10 minutes) to achieve uniform dispersion.
- Pouring and Solidification: The homogeneous mixture is poured into preheated molds and allowed to solidify under controlled cooling conditions to minimize shrinkage and segregation.

- Heat Treatment: Post-solidification heat treatment processes such as solution treatment and aging (T6 or T7 heat treatment) enhance the mechanical properties.

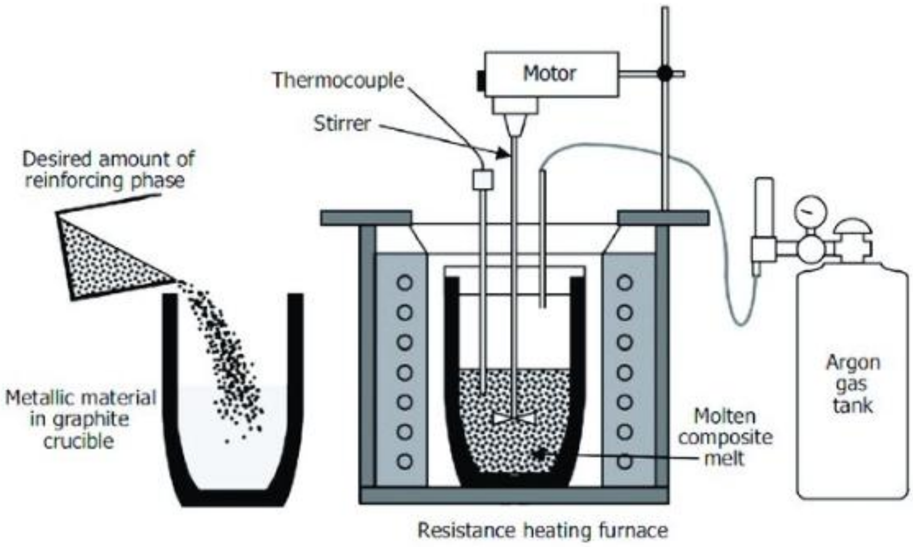

Fig 1: Typical Stir-Casting Experimental Setup

Stir casting is advantageous due to its simplicity and scalability; however, challenges like particle clustering, interfacial bonding issues, and porosity formation need to be mitigated through process optimization.

2.3 Comparison of Manufacturing Methods

Each of these methods has unique advantages and limitations, as summarized in the table 1 below:

Table 1: Comparison of Manufacturing Methods

Manufacturing Method	Advantages	Limitations
Powder Metallurgy	Fine microstructural control, low-temperature processing, minimal oxidation	High porosity, limited part size, requires secondary processing
Stir Casting	Cost-effective, suitable for large-scale production, simple setup	Particle clustering, porosity, requires post-processing

The choice of manufacturing process depends on the intended application, cost considerations, and required material properties. Stir casting is well-suited for bulk production, while powder metallurgy offers precise control for specialized applications [19-21]. Further process optimization and hybrid manufacturing approaches may be explored to enhance the performance of AA 7068/ZrO_2/Fly Ash composites.

3. Materials Used in Hybrid Composites

Hybrid composites consist of multiple reinforcing phases embedded within a matrix material to achieve superior mechanical, thermal, and tribological properties. The selection of appropriate matrix and reinforcement materials is crucial for optimizing the performance of the composite in industrial applications. In this study, AA 7068 aluminum alloy serves as the matrix material, while zirconium dioxide (ZrO_2) and fly ash act as reinforcements [22]. Each of these materials plays a significant role in enhancing the composite's overall strength, wear resistance, weight reduction, and sustainability.

3.1 AA 7068 Alloy

AA 7068 is one of the highest-strength aluminum alloys, specifically designed for applications demanding exceptional mechanical strength, fatigue resistance, and corrosion resistance as shown in figure 2. It is commonly used in aerospace, military, and high-performance automotive industries due to its excellent strength-to-weight ratio. The high zinc (Zn) content in AA 7068 provides significant strengthening through solid solution and precipitation hardening mechanisms [23-25].

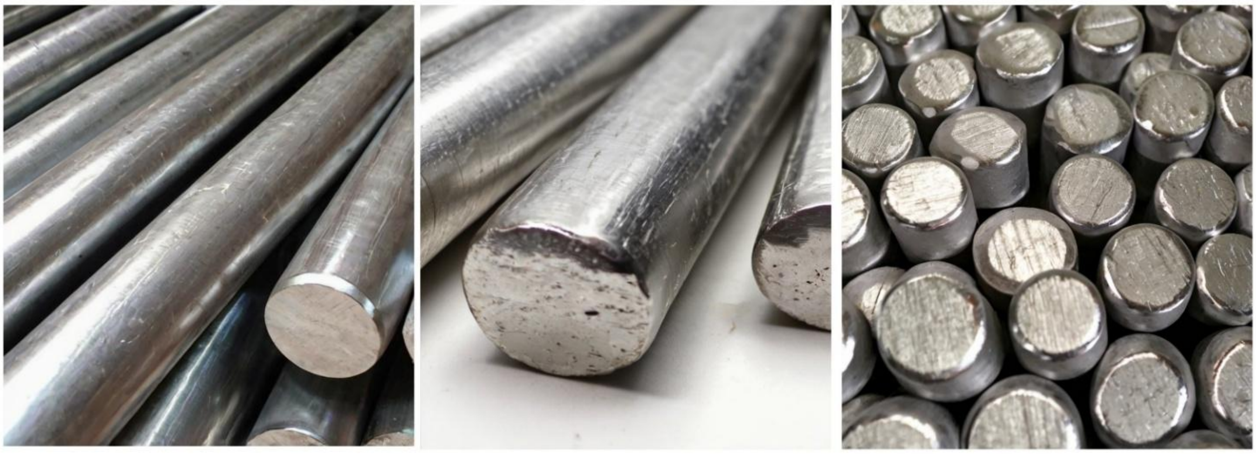

Fig 2: Round Aluminium Alloy 7068 Bars, Grade: 7075, Size: 30 mm

3.1.1 Chemical Composition of AA 7068

The composition of AA 7068 is given in Table 2, where zinc (Zn) is the dominant alloying element, followed by magnesium (Mg), copper (Cu), and zirconium (Zr). These elements contribute to the superior mechanical and thermal properties of the alloy.

Table 2: Chemical Composition of AA 7068 Alloy [26]

Element	Composition (%)	Role in Alloy
Zinc (Zn)	7.3 – 8.3	Provides solid solution and precipitation strengthening
Magnesium (Mg)	2.3 – 3.3	Improves corrosion resistance and enhances strength
Copper (Cu)	1.6 – 2.4	Increases hardness and mechanical properties
Zirconium (Zr)	0.05 – 0.15	Refines grain structure and enhances toughness
Iron (Fe)	≤ 0.15	Impurity element that may affect toughness
Silicon (Si)	≤ 0.12	Affects castability and corrosion resistance
Other Elements	Trace amounts	Control specific material properties

3.1.2 Mechanical Properties of AA 7068

AA 7068 exhibits superior mechanical properties compared to other aluminum alloys, making it suitable for applications that require high strength and fatigue resistance. The mechanical properties of AA 7068 in different processing conditions (as-cast, solution-treated, and aged conditions) are listed in Table 3.

Table 3: Mechanical Properties of AA 7068 Alloy [27]

Property	As-Cast Condition	Solution-Treated (T6) Condition	Aged (T7) Condition
Tensile Strength (MPa)	600 – 650	700 – 750	590 – 630
Yield Strength (MPa)	550 – 600	650 – 700	560 – 600
Elongation (%)	6 – 8	8 – 10	7 – 9
Hardness (HV)	160 – 180	190 – 210	180 – 200
Fatigue Strength (MPa)	250 – 300	350 – 400	300 – 350

AA 7068 exhibits high tensile strength, making it ideal for load-bearing aerospace and defense components. The solution-treated (T6) condition significantly enhances its strength, while aging (T7) improves its fatigue resistance. Additionally, it maintains reasonable ductility, allowing for deformation without catastrophic failure.

3.1.3 Corrosion and Wear Resistance

AA 7068 has superior corrosion resistance compared to other high-strength aluminum alloys due to its low iron and silicon content. The presence of magnesium further improves its resistance to environmental degradation, especially in marine and aerospace environments. The wear resistance of AA 7068 is moderate, but it can be enhanced by incorporating ceramic reinforcements such as ZrO_2 and particulate reinforcements like fly ash, which reduce wear rates and improve the tribological behavior of the composite as shown in Table 4.

Table 4: Corrosion and Wear Properties of AA 7068 [28]

Property	AA 7068 Alloy	Hybrid AA 7068/ZrO_2/Fly Ash Composite
Corrosion Resistance	High	Higher due to ZrO_2 and fly ash passivation
Wear Rate (mm^3/Nm)	1.2 – 1.5	0.8 – 1.0 (lower due to ceramic reinforcement)
Friction Coefficient	0.35 – 0.40	0.25 – 0.30 (reduced due to ZrO_2)

AA 7068 is a high-performance aluminum alloy with exceptional mechanical strength, corrosion resistance, and fatigue durability. These properties make it a preferred choice for aerospace, defense, and high-performance engineering applications. However, by incorporating ZrO_2 and fly ash reinforcements, its mechanical and wear properties can be further enhanced, leading to the development of lightweight, high-strength hybrid composites.

3.2 Zirconia (ZrO_2)

Zirconia (ZrO_2) is a ceramic material renowned for its exceptional mechanical properties, which include high hardness, superior wear resistance, and excellent thermal stability as shown in figure 3. These properties make zirconia an ideal material for use in various high-performance applications, including the enhancement of composite materials [29].

Fig 3: Zirconia Powder

3.2.1 Hardness and Wear Resistance

Zirconia's hardness is one of its most defining features. It ranks high on the Mohs scale of mineral hardness, typically between 8 and 8.5, making it harder than many other materials as shown in table 5. The hardness of zirconia enables it to resist surface wear and maintain its structural integrity under harsh operating conditions. This is particularly valuable in applications where the material is subjected to abrasion, such as in cutting tools, ball bearings, and other industrial components. The high wear resistance of zirconia helps extend the lifespan of composite materials that incorporate it. In situations where materials are exposed to friction or abrasive forces, zirconia acts as a protective phase, preventing rapid degradation and ensuring the composite remains functional over time.

Table 5: Zirconia Properties – Hardness and Wear Resistance [30]

Property	Zirconia (ZrO_2)
Hardness (Mohs scale)	8-8.5
Wear Resistance	High
Typical Applications	Cutting tools, bearings, wear-resistant components

3.2.2. Thermal Stability

Zirconia exhibits excellent thermal stability, meaning it retains its mechanical properties even at elevated temperatures as shown in table 6. It has a high melting point of around 2,700°C (4,892°F), making it suitable for applications that involve thermal cycling or exposure to high-temperature environments. One of the significant advantages of zirconia in composite materials is its ability to withstand temperature fluctuations without undergoing significant thermal expansion. This property is particularly useful in aerospace and automotive industries, where materials are frequently subjected to extreme temperature conditions. Zirconia's low thermal conductivity also contributes to its effectiveness as an insulating material.

Table 6: Zirconia Properties – Thermal Stability [31]

Property	Zirconia (ZrO_2)
Melting Point	2,700°C (4,892°F)
Thermal Conductivity	Low
Thermal Expansion	Low
Typical Applications	Aerospace, automotive, high-temperature components

3.2.3. Toughness and Load-Bearing Capacity

Although ceramics are generally known for their brittleness, zirconia stands out due to its exceptional toughness. This toughness is a result of the material's ability to undergo phase transformation under stress. When subjected to mechanical forces, zirconia can transition from a tetragonal phase to a monoclinic phase, which helps absorb and dissipate energy. This phase transformation prevents the initiation of cracks and delays fracture propagation, thus increasing the material's resistance to failure under load. When incorporated into composite materials, zirconia enhances the overall load-bearing capacity of the composite, making it more suitable for structural applications where high strength and durability are required as shown in table 7. This property is particularly beneficial in industries like aerospace and defense, where materials must endure extreme loads without failure.

Table 7: Zirconia Properties – Toughness and Load-Bearing Capacity [32]

Property	Zirconia (ZrO_2)
Toughness	High
Load-Bearing Capacity	High
Phase Transformation	Tetragonal to Monoclinic
Typical Applications	Aerospace, defense, structural components

Zirconia (ZrO_2) is a versatile ceramic material that significantly improves the performance of composite materials by enhancing their hardness, wear resistance, thermal stability, and load-bearing capacity. Its inclusion in composites ensures that the material can withstand extreme conditions without failure, making it suitable for a wide range of demanding applications in industries such as aerospace, automotive, and medical devices. The unique combination of properties offered by zirconia makes it an indispensable component in advanced materials engineering.

3.3 Fly Ash

Fly ash is a byproduct of coal combustion in power plants, consisting of fine particles that are captured by electrostatic precipitators or filter bags as shown in 4. It is widely used as a reinforcement material in various composite systems due to its ability to reduce the overall density of the composite while also enhancing its thermal insulation properties. The inclusion of fly ash in composites contributes to both sustainability and cost-effectiveness, making it an attractive choice for a variety of applications [33].

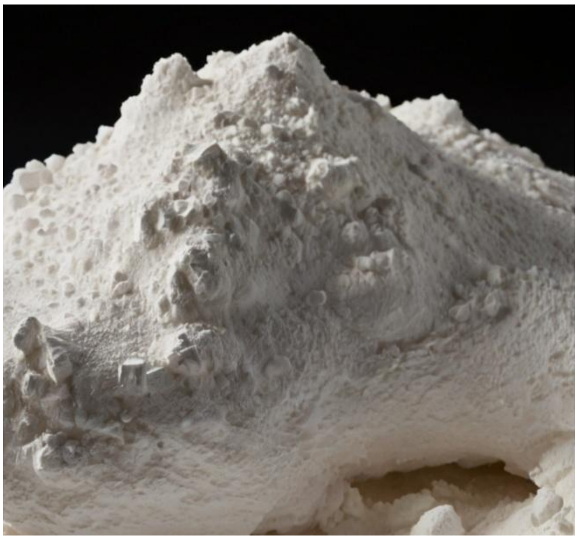

Fig 4: Fly Ash

3.3.1 Reduction in Density

One of the key advantages of using fly ash as a reinforcement is its ability to reduce the overall density of composite materials. Fly ash particles are lightweight, which helps lower the mass of the final composite without compromising its mechanical properties as shown in table 8. This is particularly useful in industries such as aerospace, automotive, and construction, where the reduction of weight is a critical design factor for improving performance and fuel efficiency. By reducing the density of composites, fly ash helps make materials more energy-efficient and environmentally friendly, contributing to the overall reduction of greenhouse gas emissions in industries where lightweight materials are in high demand.

Table 8: Fly Ash Properties - Density Reduction [34]

Property	Fly Ash
Density	Low
Effect on Composite	Reduces overall density
Typical Applications	Aerospace, automotive, construction

3.3.2. Thermal Insulation

Fly ash also contributes to the thermal insulation properties of composites as shown in table 9. Due to its porous nature and low thermal conductivity, fly ash helps improve the composite's resistance to heat transfer. This property is particularly valuable in applications where thermal insulation is critical, such as in construction materials, insulation panels, and protective coatings. The inclusion of fly ash improves the ability of the composite material to withstand high temperatures, making it suitable for use in environments with significant temperature fluctuations or heat exposure. The thermal stability of fly ash-reinforced composites is further enhanced when combined with other materials that provide additional resistance to thermal degradation.

Table 9: Fly Ash Properties - Thermal Insulation [35]

Property	Fly Ash
Thermal Conductivity	Low
Effect on Composite	Enhances thermal insulation
Typical Applications	Insulation panels, construction materials

3.3.3. Sustainability and Cost-Effectiveness

The use of fly ash in composites supports sustainability by reducing the demand for natural resources. Since fly ash is a waste byproduct from coal combustion, incorporating it into composites helps divert this material from landfills, contributing to waste reduction and recycling efforts. By using fly ash, industries can create value from an otherwise discarded material, leading to more sustainable manufacturing practices as shown in table 10. Fly ash is also cost-effective, as it is generally less expensive than many other reinforcement materials. Its availability as a byproduct makes it a low-cost option for enhancing the properties of composites, helping reduce overall material costs and increasing the economic feasibility of composite production. This makes fly ash an attractive choice for manufacturers looking to produce high-performance materials at a lower cost.

Table 10: Fly Ash Properties – Sustainability and Cost-Effectiveness [36]

Property	Fly Ash
Source	Byproduct of coal combustion
Environmental Impact	Reduces landfill waste, promotes recycling
Cost Effectiveness	Low-cost reinforcement
Typical Applications	Construction, manufacturing, waste reduction

Fly ash, a waste byproduct from coal combustion, plays a crucial role in enhancing the properties of composite materials by reducing density, improving thermal insulation, and promoting sustainability. Its incorporation into composites results in cost-effective, lightweight, and thermally stable materials suitable for a wide range of applications in construction, automotive, and manufacturing industries. By utilizing fly ash, industries can contribute to waste reduction efforts while simultaneously producing high-performance composite materials at a lower cost, making it an environmentally friendly and economically viable option.

4. Mechanical and Thermal Properties

The mechanical and thermal properties of AA 7068, ZrO_2, and Fly Ash are critical to understanding how these materials behave individually and contribute to the overall performance of the hybrid composite. Below is a breakdown of the key properties of each material, which can later be used to analyze the composite behavior once combined.

4.1. Mechanical Properties

The tensile strength, hardness, and impact resistance of the materials provide key insights into their overall mechanical performance as shown in figures 5, 6, and 7. Tensile strength indicates how much stress a material can withstand before breaking, making it vital for load-bearing applications. Hardness measures the material's resistance to localized deformation or scratching, reflecting its wear resistance and durability under surface contact. Impact resistance, on the other hand, assesses a material's capacity to absorb energy and withstand sudden shocks or dynamic loads without fracturing. Collectively, these three properties guide engineers and researchers in selecting the most suitable material for specific structural, wear-intensive, or high-impact environments.

4.1.1 Tensile Strength

- AA 7068: AA 7068 is a high-strength aluminum alloy, known for its excellent tensile strength, which makes it ideal for applications in aerospace and defense. This alloy provides a strong base for composites, supporting high tensile forces.
- ZrO_2: ZrO_2 (Zirconia) is a ceramic material with exceptional hardness and strength. It contributes significantly to the tensile strength of composites by enhancing the overall structural integrity.
- Fly Ash: Fly Ash is a lightweight, mineral filler material that typically does not contribute significantly to tensile strength but reduces the overall weight of composites, making them more efficient in load-bearing applications [37].

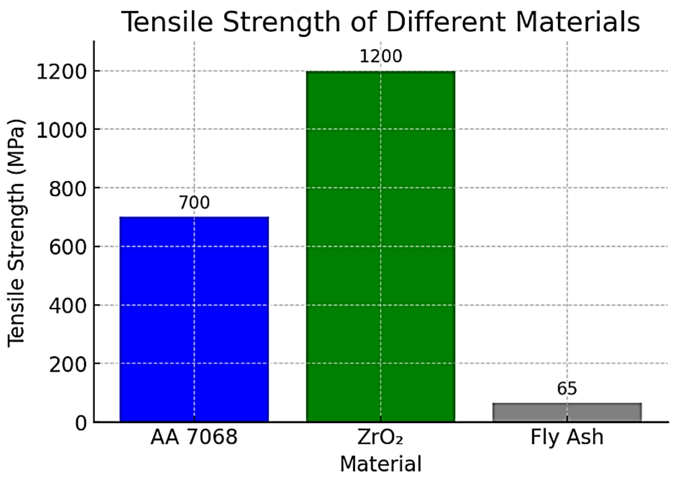

Fig 5: Tensile Strength of Individual Materials

4.1.2 Hardness

- AA 7068: AA 7068 has good hardness, though it is not as hard as ceramics. The hardness of this alloy ensures that it can withstand moderate wear in general applications.
- ZrO_2: ZrO_2 is a ceramic material with very high hardness, making it resistant to wear and abrasion. This property is especially useful in composites that need to endure harsh environmental conditions.
- Fly Ash: Fly Ash is generally softer than metals and ceramics. It serves primarily as a lightweight filler and does not significantly impact hardness [38].

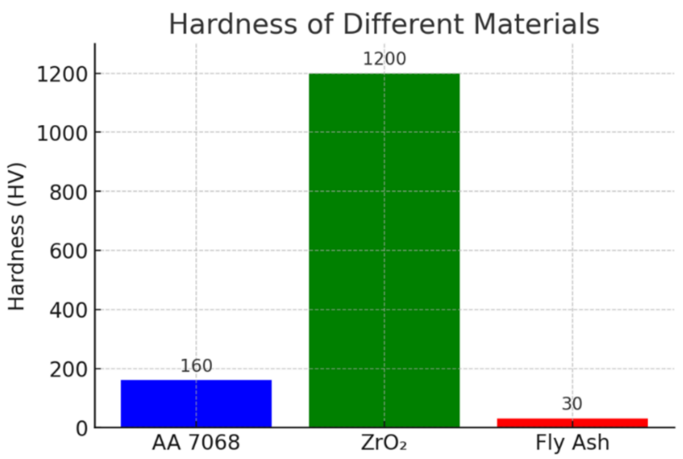

Fig 6: Hardness Comparison of Individual Materials

4.1.3 Impact Resistance

- AA 7068: The high tensile strength of AA 7068 is complemented by a decent impact resistance, allowing the material to absorb shock forces effectively without brittle fracture.
- ZrO_2: ZrO_2 has high impact resistance due to its toughness. However, it can become brittle under certain conditions, which is why it is often used in small amounts as reinforcement in composites.

- Fly Ash: Fly Ash generally does not contribute much to impact resistance, but its presence helps in reducing the overall weight of the composite material, which can be beneficial in dynamic applications [39].

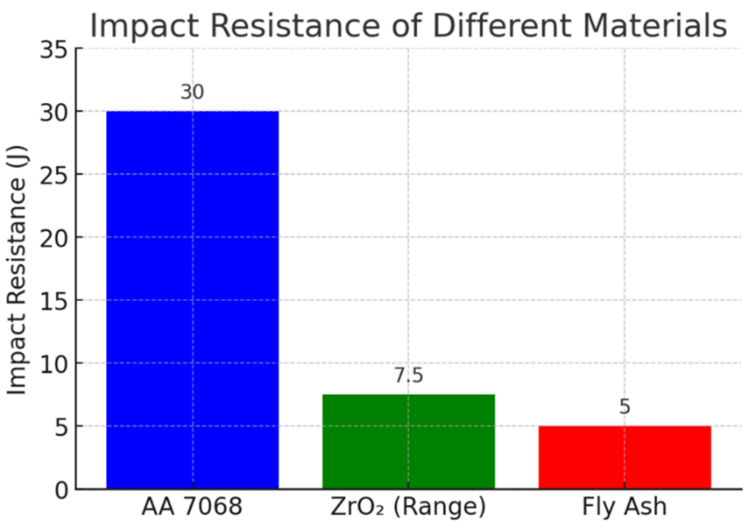

Fig 7: Impact Resistance of Individual Materials

4.2. Thermal Properties

Thermal conductivity is a critical property that defines a material's ability to transfer heat, playing a pivotal role in applications ranging from thermal management in electronics to insulation in construction as shown in figure 8. It quantifies how efficiently heat is conducted through the material and influences the overall energy efficiency and performance of systems. Materials with high thermal conductivity are typically used where rapid heat dissipation is required, while those with lower values are chosen for their insulating properties. Understanding and comparing thermal conductivity values helps in designing and optimizing products to meet specific thermal performance criteria.

4.2.1 Thermal Conductivity

- AA 7068: AA 7068 has relatively high thermal conductivity, making it suitable for applications where heat dissipation is important.
- ZrO_2: ZrO_2 has low thermal conductivity, which is an advantage for insulation and thermal management applications.
- Fly Ash: Fly Ash also has low thermal conductivity, making it an effective thermal insulator when incorporated into composites [40].

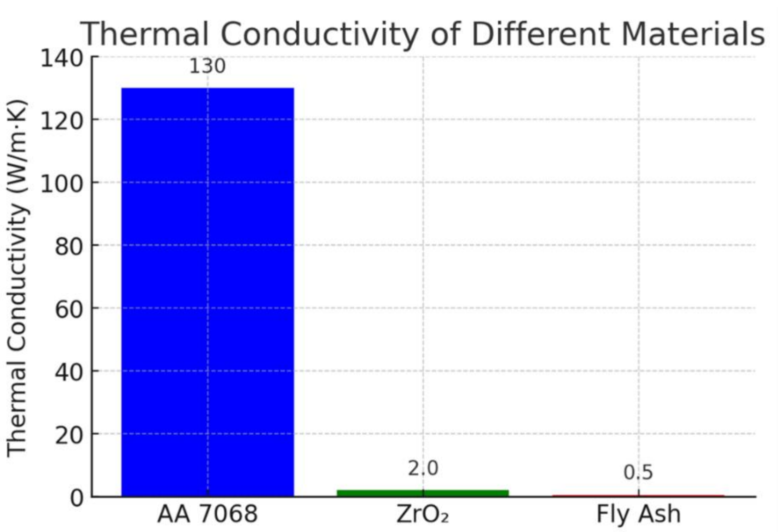

Fig 8: Thermal Conductivity of Individual Materials

The individual properties of AA 7068, ZrO_2, and Fly Ash contribute in unique ways to the performance of hybrid composites. AA 7068 offers high tensile strength, moderate hardness, and good impact resistance. ZrO_2 provides exceptional hardness, impact resistance, and thermal stability, while Fly Ash acts as a lightweight filler that reduces density and improves thermal insulation. Understanding these individual properties is crucial for predicting how these materials will perform in a composite and how their combination can lead to improved overall properties for specific applications.

5. Applications of AA 7068, ZrO_2, and Fly Ash

The materials AA 7068, ZrO_2, and Fly Ash each have unique properties that make them suitable for various applications across different industries. Below are the individual applications of each material in specific sectors:

5.1 Aerospace Structures
- AA 7068: Due to its high strength-to-weight ratio, AA 7068 is extensively used in aerospace structures, such as aircraft frames, wings, and landing gear components. The alloy's ability to withstand high stress while remaining lightweight makes it ideal for aerospace applications.
- ZrO_2: ZrO_2 is not typically used directly in structural aerospace components but can be used for high-performance coatings and thermal barriers. Its high thermal stability makes it an ideal material for protecting critical components from high heat in aerospace engines and exhaust systems.
- Fly Ash: Fly Ash is not typically used in structural aerospace components due to its relatively low strength, but it can be incorporated into lightweight composites for non-load-bearing parts. Fly ash is also explored for potential use in thermal insulation or heat-resistant coatings in the aerospace industry [41-42].

5.2 Automotive Components
- AA 7068: AA 7068's high strength and light weight make it ideal for high-performance automotive applications, such as engine parts, chassis components, and suspension systems. It helps in improving the fuel efficiency of vehicles by reducing weight while maintaining structural integrity.
- ZrO_2: ZrO_2 is often used in automotive applications for wear-resistant coatings, particularly in engine components like valves and cylinder heads, as well as in exhaust systems due to its excellent resistance to thermal shock and high temperatures.
- Fly Ash: Fly Ash can be used as a filler material in automotive composites to reduce weight and improve thermal insulation. It is also used in the production of lightweight concrete for automotive infrastructure, such as crash barriers or insulation materials [43-44].

5.3 Marine Applications
- AA 7068: In the marine industry, AA 7068 is used in the construction of ships, submarines, and other marine vessels where high-strength, corrosion-resistant materials are required. Its resistance to seawater corrosion makes it a suitable choice for marine applications.
- ZrO_2: ZrO_2 is used in marine applications for its corrosion resistance and wear resistance, particularly in marine engine components and underwater equipment that are exposed to harsh seawater environments. ZrO_2 coatings are also used to protect against biofouling.
- Fly Ash: Fly Ash, due to its lightweight and insulating properties, can be used in marine applications for constructing low-density materials for ships or offshore structures. It is also explored in creating eco-friendly composites for marine environments [45-46].

5.4 Biomedical Implants
- AA 7068: AA 7068 is suitable for biomedical implants such as orthopedic devices and prosthetics due to its high strength-to-weight ratio and biocompatibility. It is used in applications requiring a combination of strength, durability, and low weight.
- ZrO_2: ZrO_2 is widely used in biomedical implants, particularly in dental implants, hip replacements, and prosthetic joints. It is highly biocompatible, has excellent wear resistance, and is known for its resistance to corrosion in biological environments.
- Fly Ash: Fly Ash is not typically used in direct biomedical implants but may be explored in regenerative medicine, tissue engineering scaffolds, or composite materials for drug delivery systems. Its lightweight and biocompatible nature make it a potential candidate for certain biomedical applications [47-48].

Each of the materials AA 7068, ZrO_2, and Fly Ash plays an important role in various industries. AA 7068 is primarily used in aerospace, automotive, and biomedical applications due to its high strength and light weight. ZrO_2 finds use in coatings, wear-resistant applications, and biomedical implants, owing to its hardness and thermal stability. Fly Ash, while not typically used in structural applications, provides valuable benefits when used as a lightweight filler in composites and as a thermal insulator in various sectors. The unique properties of each material allow them to be used individually in specific applications, or they can be combined to create hybrid composites for enhanced performance [49].

6. Future Potential
The future potential of AA 7068, ZrO_2, and Fly Ash hybrid composites is highly promising. These materials, when combined, already offer an excellent balance of strength, wear resistance, and thermal stability. As these composites continue to be refined, their properties will only improve, making them even more suitable for demanding applications in aerospace, automotive, and biomedical industries. By optimizing the manufacturing processes and exploring new ways to enhance the interaction between the matrix and reinforcements, the overall performance of these composites can be further elevated. The hybrid composites offer a unique combination of lightweight, strength, and durability, ensuring that they

will continue to be an ideal choice for high-performance applications. As advancements in processing techniques continue, these composites will provide superior solutions for applications requiring both mechanical strength and thermal stability.

7. Conclusion

The study of hybrid AA 7068, ZrO_2, and Fly Ash composites has demonstrated their significant potential as high-performance materials, offering a unique combination of strength, wear resistance, and thermal stability. The blend of these materials creates a composite that excels in various demanding applications, including aerospace, automotive, and biomedical sectors. The inclusion of ZrO_2 enhances the composite's toughness and wear resistance, while Fly Ash contributes to sustainability by reducing density and improving thermal insulation. The hybrid nature of these composites allows for tailored properties, making them versatile for a range of uses that require both mechanical and thermal performance. Continued research and development in processing techniques, material optimization, and the exploration of new reinforcement materials will drive further advancements in this field. By focusing on refining manufacturing processes, improving the interfacial bonding between the matrix and reinforcements, and exploring new applications, the performance of these composites can be further enhanced. As the understanding of these hybrid materials deepens, their use will expand, providing innovative solutions for industries looking for high-performance, sustainable, and cost-effective materials.

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