Review

AA7075-ZrO₂ Nanocomposites Produced by the Consecutive Solid-State Process: A Review of Characterisation and Potential Applications

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Abstract: Solid-state recycling is a direct conversion method for producing metal chips, whereas the materials are plastically deformed into the final product without melting, offering lower energy consumption and metal waste. This technique was reported for fabricating aluminium-zirconium oxide (Al-ZrO₂) composite and it was widely used to avoid metal chips bounding at high temperatures during the extrusion process. Aluminium alloy (AA7075) is known for its high yield strength of more than 500 MPa under optimum ageing conditions. However, AA7075 can be further reinforced by zirconium oxide nanoparticles when needed for high-performance applications. Hot extrusion is used to obtain better mechanical properties of composite materials. The equal channel angular pressing (ECAP), a severe plastic deformation technique, was recently used to produce bulk and light recycled metal chips, such as porosity-free and ultra-fine-grained aluminium nanocomposites (ANCs). Heat treatments (HT) and ECAP post hot extrusion are mostly incorporated to improve tribological and mechanical properties and aluminium nanocomposite bonding efficiency. In this review, ANCs' fabrication by the hot extrusion technique and the effects of ZrO₂ nanoparticle are duly summarised and discussed. Furthermore, this review emphasises the importance of using HT and ECAP techniques to acquire better metal alloy incorporation, such as AA7075-ZrO₂. Interestingly, owing to the lightweight properties and superior performance of AA7075-ZrO₂, it was reported to be suitable for fabricating many drones' parts, military equipment, and some other promising applications.

Keywords: AA7075; ECAP; hot extrusion; solid state recycling; zirconium oxide

1. Introduction

Aluminium alloys constitute the bulk of modern structural materials that are deployed in a variety of engineering applications, including aerospace, automotive, marine, and military [1], primarily because of their low density and favourable mechanical properties [2]. The promising competitive advantages of aluminium in industrial applications and the excellent machinability are part of this review's motivation. Earlier studies forecast a global average annual increase of 20% in demand for aluminium alloys, being justified by the vast areas of aluminium alloy applications (as presented in Table 1).

Aluminium alloys are broadly categorised into two major classes: cast alloys and wrought alloys. In the classification of heat treatment, these alloys are further divided into heat treatable and non-heat-treatable alloys [3].

Table 1. The uses and areas of application of aluminium alloys.

Aluminium Alloy	Use of Alloy
7075	Construction materials and aerospace (wings and fuselage).
1050/1200	Food and chemical industry.
2014	Airframes.
5214/5052	Vehicle panelling, marine-exposed buildings, habitats, mining cages.
6063	Architectural extrusions (internal and external), window frames, irrigation pipes.
6061/6082	Stressed members of the framework, bridge, roof truss cranes, beer barrels.

The low melting point temperature of cast aluminium alloys ($\sim 655^\circ\text{C}$) places these alloys at a cost-effective position on the production method hierarchy [4,5]. The inherent properties of aluminium when alloyed with other metals result in better mechanical properties, such as improved strength, hardness, and corrosion resistance, in addition to the lightweight properties of aluminium [6]. The need for improved physical and mechanical properties of aluminium alloys is central to the expansion of recycled aluminium applications [7]. The conversion of chips to different engineering applications is carried out using two common methods, which are liquid metallurgy (LM) and powder metallurgy (PM) [8]. The main aim of producing recycled reinforced aluminium metal is to take advantage of the attractive properties of aluminium and the reinforcing material to form a unique composite material [9]. A collection of aluminium alloys in various shapes have been used in the formation of MMCs (Metal Matrix Composites) [10], with the formation of precipitation hardening particles that improved the strengths of the 6xxx and 7xxx alloy series. This development broadens the areas of application, which makes it possible for these alloys to replace steel [11,12].

The 7xxx series alloys are known as aluminium-zinc alloys; hence the major alloying element is Zn which ranges from 5.1 wt.% to 6.1 wt.% (weight fraction) of chemical composition [13]. When aluminium alloy was used as the matrix material (continuous phase), the properties were enhanced by adding desirable single and multiple reinforcement particulates [14]. AA7075 is used in aerospace wings and fuselage components, and it is also used to manufacture rock climbing equipment and bicycle components [15,16]. The composition of AA7075 was reported to be 5.6–6.1 wt.% Zn, 2.1–2.5 wt.% Mg, 1.2–1.6 wt.% Cu, 0.5 wt.% Fe, 0.4 wt.% Si, 0.3 wt.% Mn, 0.2 wt.% Ti, and 0.18–0.28 wt.% Cr [17]. The excellent thermal conductivity, good workability, high machinability, increased corrosion resistance, and low costs are the main reasons for the use of AA7075 [18]. Imran and Khan [19] reported that the mechanical, physical, and tribological properties of AA7075 metal matrix composite were improved by heat treatment, which, in return, can vary with the used components and the filler materials.

Aluminium-based metal matrix composites (AMMCs) have been developed to satisfy the demands for wear resistance, high stiffness, high strength, and enhanced fracture toughness [20], and AMMCs are fabricated using various techniques, like powder metallurgy, plasma spraying, spray atomisation casting, and stir and squeeze casting [21]. However, most of the previous works on AMMCs were limited to micron size reinforcement particles [21–25]. At present, research on AMMCs focuses on the use of nano-sized reinforcement particles due to the tendency of nanoparticles to mix with the base alloy when compared to microparticles, thus improving the performance of the composite materials. Besides, nanocomposites have been found to possess enhanced strength with a good amount of ductility [26,27]. Solid-state recycling is a method involving five major stages to produce recyclable aluminium metal from waste chips through to the preparation of the final product [28]. The method adopted depends on desired properties with parameters such as chip size, cold-pressing parameters, extrusion temperature, extrusion rate, and ratio, which influence the mechanical properties of aluminium chips [4].

Nanoparticles (NP) have been acknowledged as one of the most promising materials for their unique surface area to volume ratio. Zirconium oxide nanoparticles are among the functional nanoparticles used in tooth coating, cosmetic products, and many other

industrial applications [29]. The addition of zirconium oxide nanoparticles has been reported to improve the mechanical properties and expand the application of recycled aluminium chips [30]. The end material was cheaper using the solid-state recycling of scraps from machining operations through hot forward extrusion.

Aluminium 7075 alloy composites can be used in the treated, lightweight transmission gears. Such transmissions properties can potentially be used in drones or military robots [31]. However, the literature on the physical and mechanical properties of the AA7075 composite and the application of ECAP and HT following metal fabrication by hot extrusion was not covered or reviewed elsewhere, despite the importance of its emerging applications. In the current review, ANCs manufacturing techniques and the effect of ZrO_2 nanoparticle addition on the morphology, microstructure, physical, and mechanical properties of AA7075- ZrO_2 are covered and extensively discussed.

2. Recycling Aluminium Techniques

Recycled aluminium techniques were used to augment the supply of aluminium alloys, such as sheets, plates, channels, and rods, for various engineering applications and reduce the energy demand in the bauxite to aluminium process [32]. The reported study considered the reprocessing of solid wastes of aluminium scraps to obtain improved properties. The powder metallurgy technique and solid-state recycling are the two main standard recycling techniques [33]. The solid-state technique was found to be more suitable for the Al- ZrO_2 , as chips were reported to be bound at high temperatures during the extrusion process.

2.1. Solid-State Recycling Method (Conversion Method)

Solid-state recycling offers a low energy consumption and metal loss [34]. It is a method of recovering metal chips through direct conversion, whereas materials are plastically deformed into the final product without melting. In this method, metal chips are pulverised, then cleaned and dried. Next, the dried chips are cold compacted and hot extruded before the resulting piece is cut to the desired length. The mechanical properties of aluminium processed by solid-state recycling method are affected by a few factors such as type of chips, heat treatment, die design, and other processing factors [8,35]. Shamsudin et al. [8] reported that solid-state recycling or direct conversion of aluminium and its alloys contribute to environmental protection as carbon footprints caused by extraction of aluminium from its ores and secondary processes are reduced. Thus, direct conversion is considered a better recycling route than conventional recycling. The direct conversion of aluminium scrap into a compact metal saves 40% material, 26–31% energy, and 16–60% labour; however, the conventional recycling process showed higher mechanical and physical properties with improved microstructure and chemical compositions [35]. The potentials that are displayed by the technique and the ease of processing served as evidence of the deployment of the direct solid-state method, with the ECAP aimed at strengthening the observed weakness of the direct conversion processes.

2.2. Powder Metallurgy Technique

Powder Metallurgy is one of the standard techniques used to fabricate lightweight metals, such as particle-reinforced metal matrix composites (PRMMCs). Powder metallurgy techniques, such as stir casting technique, infiltration techniques, compo-casting technique, and ultrasonic cavitation, are mainly based on solidification techniques [8]. The ability to fabricate advanced elements is the significant economic advantage of this process. Furthermore, this process produces low-value and high-volume products. The stages of powder metallurgy can be divided into three main steps: powder mixture, cold compaction, and sintering [32]. Wagiman et al. [36] recently performed research on recycling aluminium scraps chips using the powder metallurgy technique followed by the plastic deformation extrusion method. The method involved the conversion of scraps from AA7075 into a finished product directly without the melting process. The findings above were relevant

to the current review, showing that aluminium chips can be recycled using either the powder metallurgy or the direct recycling route. However, the study was short in terms of accessing the maximum behaviour of the composite material before and after the T6 heat treatment. Aluminium matrix composites are reinforced with ceramic nanoparticles such as ZrO_2 . The introduction of ZrO_2 allows the material to have a low coefficient of thermal expansion, good thermal shock resistance, a high melting point, low thermal conductivity, and excellent thermodynamic stability [37]. These findings were similar to those of the composite material that had a Young's modulus of 190 GPa and hardness of 200 HV, respectively, at 750 °C. Improved tensile strength was also observed alongside the characteristics that were mentioned earlier [38]. However, most of the reinforcements and composites added to form a matrix bulk material were used to increase the strength and stiffness of the matrix [39].

2.3. Conventional Recycling Method

The conventional method of processing recycled aluminium chips involves the melted alloy being recycled. This technique is known for its high energy consumption, higher operating costs, and lengthy processes, resulting in long operating times [36]. The claim of Wagiman et al. [36] outlined here was based on the fact that about 10% of the total material was lost during the initial melting process, while scraps were converted to ingots. Among those lost include the materials that may settle as slags and those that stick to the crucible. Cumulatively, about 35% of the melting process is performed in gas furnaces rather than induction [33]. The recycled aluminium that was fabricated through the direct recycling method has been reported to demonstrate high strength, because the refinement of the chips and a homogeneous hardness of oxide precipitates were obtained.

3. The Mixing Technique

Mixing is achieved when the powder metallurgy process is deployed by blending a mix of metal powder with particulate or whiskers ceramic reinforcement and placed in a mould of the desired shape. The objective of the blending is to develop a uniform distribution of particulate throughout the composite material for homogeneous reinforcement. The process was followed by the compacting of the mixture under high pressure. The hot-pressing process involves heating the die to a temperature below the metal's melting point, enough to form a significant solid-state diffusion. Sintering helps the bonding of ceramic reinforcement with the metal powder. At this stage, undesired gases are removed through a degassing process, followed by the sealing or canning of the container, which is then stripped to remove the part that had been consolidated. Other methods include pressing the mixture via cold-pressing, followed by a separate consolidation stage after the mixture is blended. The compaction level depends on the density of all the constituents that make up the composite material, as presented in Equations (1)–(4) [32].

$$\rho = m/v \quad (1)$$

$$V_c = V_r + V_m, \quad (2)$$

$$\rho_c = \rho_r + \rho_m, \quad (3)$$

$$\rho_c = M_r/V_c + M_m/V_c, \quad (4)$$

where ρ_c is the density of the composite material, ρ_r is the density of reinforcement, and ρ_m is the metal matrix 7075 aluminium alloy density. V_r and V_m are the volume fraction of the reinforcement and the metal matrix, respectively.

The above relationship is essential in providing requisite knowledge of the physical properties of the composite material understudied in the current work. This means that the density of the composite material is directly related to the density of the reinforcement and AA7075 metal matrix, and the level of compaction affects the pair.

4. Fundamentals of Hot Extrusion Process

The hot extrusion process is a widely accepted method of recycling aluminium directly from chips, eliminating the heating stage of the production process, making it flexible and cost-effective. The consolidation process of the excellent chip was accomplished by hot extrusion, as this process is capable of crushing the oxide layer across the surfaces of the chip and fostering a sufficient weld bond under an excessive strain of plastic and pressure [40]. This method allows the passage of hot, round, and hollow billet of aluminium through a forming die. While passing through the die, the hollow material is compressed due to the high temperature and it forms a single solid material that can be further processed [41]. On the other hand, forged and cold extruded products are also extruded through dies.

The primary principle of extrusion is the creation of objects with a fixed cross-sectional profile. This is accomplished by forcing the material through a predetermined die with an area that is lower than the billet size. The movement of the material through the gap naturally deforms the material into the shape through which it passes. This production process has two main advantages over other production processes.

Firstly, very complex cross-sections can be fabricated through this process; hence, brittle materials can be processed as the materials are only subjected to compressive and shear stresses. Secondly, the process form parts with an excellent surface finish [42].

In the extrusion process, the pressure is connected to the billet by the compressing ram, and the die can then compress the billet. During this process, the temperature is the most crucial parameter to be considered because the magnitude of the temperature determines the compactness and fusion of the material in the matrix. This, in effect, determines the properties of the material, such as hardness and surface finishing of the extruded part. Previous studies revealed that aluminium alloys were extruded into a round and hollow bar, demonstrating the potentialities of the process. Pre-heating temperature to around 500 °C in the furnace was also recorded in the experiments carried out [42]. The reason for the choice of hot extrusion was based on potentials, and the purpose of optimising the properties was to obtain parameters that utilise the most suitable temperature during the extrusion process.

Classification of Extrusion Process

Compacted billets are transformed into extrudates using the hot extrusion process. The two main extrusion methods are direct or indirect hot extrusion, with differing applied forces in each case. Previous studies have focused on the direct hot extrusion process [36,43,44] because the pressing force that is required by direct extrusion is higher when compared to indirect extrusion. The large contact area between the surface of the billet being compacted and the wall of the container supports the higher friction force observed in a direct hot extrusion. This force simplifies the billet surface. The high sticking status reduces in the middle of the billet, which helps to break the oxide layer on the chip surface and allows consolidation between the chips.

Conversely, indirect extrusion has rarely been applied in recycling aluminium due to the reduced friction force and restricted length of the extrudate and the hollow ramp, limiting the applied maximum load [36]. The solid temperature of the 7xxx alloys can be controlled by careful selection of the billets' chemical composition of the alloy and homogenisation conditions. Because of the dissolution in the maximum degree of the low melting alloy parts, a more significant temperature increase led to a higher deformation rate, and it is possible to boost the solidus temperature (Table 2). Furthermore, the dislocation density of the specimen deformed at higher temperatures is lower than that deformed at lower temperatures for a given strain rate and strain, as described above [45–47].

Table 2. Pre-heating sintering Temperature.

Process	Temperature	Average	Ref.
Extrusion welding	520 °C		[45]
Micro-gear extrusion	450 °C and 500 °C	450 °C, 500 °C, and 550 °C	[46]
post-fire elastic modulus	450 °C, 500 °C, and 550 °C		[47]

5. Principles of Severe Plastic Deformation (SPD)

The severe plastic deformation (SPD) technique of processing light materials has been intensively used in recent years, because the method offered improved mechanical and physical properties of recycled materials. The technique revealed an intense deformation in plastic materials, resulting in the minimal distortion of microstructures and pores and reduced grain size to the micro- or nanoscale. However, SPD is still defined as a light metal forming technique where very high strains are applied without any significant changes in the overall shape and dimensions of the product, resulting in ultra-fine grain refinement. This is the cause of greater deformation in the matrix of composite materials, in which the products showed superior mechanical and physical properties [9]. Metal can be fabricated at lower temperatures using SPD consolidation, making it suitable for particles with highly metastable structures such as nanocrystal materials. It is beneficial in the fabrication of multiphase reinforced materials, including metal matrix nanocomposites. Severe plastic deformation induced a high dislocation density [48]. Severe plastic deformation of the extrudate occurs in a way similar to channel angular extrusion (CAE); thus, an extensively promoted practical strain level is achieved, although it is not always uniform across a section [49].

There are several techniques that are associated with SPD, including equal channel angular pressing (ECAP) hot extrusion, multiaxial deformation, conformation, twist extrusion, friction extrusion, high-pressure torsion, forging, accumulative roll bonding, rolling, and other methods. A common SPD technique is the equal channel angular pressing (ECAP), which uses the ECAP die at different angles [50]. The ECAP is flexible and it has been deployed in combination with hot extrusion, which led to the choice of ECAP in combination with hot extrusion. More recently, some newly developed SPD techniques, such as curved profile extrusion (CPE) [51], sideways extrusion [52], multi-hole extrusion [53], and injection forging [54], are being used for metal fabrication.

5.1. Equal Channel Angular Pressing (ECAP)

The main purpose of ECAP is to produce composite materials with high mechanical properties and enhance the strain of billets. This process has been implemented to study its effect on light metals and alloys of aluminium, copper, and titanium. Previous research on ECAP focused on metallic alloys, pure metals, and plastic deformation [55]. In recent times, the process has gained acceptance for the fabrication of metals, increasing the level of application in the industries. ECAP is an attractive method, because it can produce large samples using plastic deformation [56]. It has been reported that the mechanical behaviour of the developed chip-based nanocomposite is affected by the ECAP process. Therefore, it has become imperative to investigate the effect of the ECAP operations on the properties of the composite material. The choice of the technique was based on the level of acceptability of ECAP for industrial applications. The cast was conducted using a hybrid composite of samples with a diameter of 10 mm and length of 80 mm. The product was annealed for 4 h using 400 °C temperature to homogenise the microstructure. After the annealing, a two-channel ECAP die was used for further treatment of the composite. The channels had the same circular cross-section with a diameter of 10 mm. The two channels of intersecting the model at the inner and outer corners of $\varphi = 120^\circ$ and $\psi = 12^\circ$, respectively. According

to the theoretical geometry of the mould, the effective strain is represented by the following Equation (5) [57]:

$$\epsilon = 1/\sqrt{3}(2 \cot((\varphi + \psi)/2) + 1/\sqrt{3}(\Psi \csc(2 \cot((\varphi + \psi)/2)) \quad (5)$$

where, ϵ = the effective strain, Ψ = outer angle, and Φ = inner angle.

There are four schematic dies (routes A, B, B, and C) for ECAP passes. The differences between routes A, B, and C are the shearing directions that route B is an excellent processing route, especially for equiaxed ultra-fine microstructures.

The ECAP technique is being used to manufacture many materials within different industrial fields, such as automotive, procedures, and instruments in the medical facility, and the assembly of microelectromechanical components, including the distinct shape of memory alloy. The commercialisation of products implemented with the ECAP technique is currently undergoing extensive research. Figure 1 depicts the sequence of the chip pre-processing before and after the consolidation.

Figure 1. Pre-processing of chips before and after consolidation.

5.2. ECAP Die Construction and Design

ECAP has been reported to be suitable for the development of ultra-fine grain reinforced materials and has resulted in an enhancement of the design for better light material performance quality, and it is one of the direct recycling techniques, as shown in Table 3. Two independent studies reported ECAP as an attractive tool, as it offered a high potential strain rate and superior plasticity in the microstructure of nanostructured materials [56,58]. The technique was applied in the investigation of AMMC materials, including the use of boron carbide particles in the aluminium matrix. Particles of materials, such as copper, magnesium, nickel, and intermetallic materials, were also used in the aluminium matrix with ECAP as fabrication methods [59].

Table 3. Miscellaneous Methods in Direct Recycling Technique.

Materials	Method	Finding	Ref.
Semi-Solid Stir Casting and Rolling Method			
A356	Semi-solid stir casting and rolling method	Improved the distribution of fine SiC (Silicon Carbide) particles and eliminated remaining porosity after the first step of the casting process. Examination of the mechanical properties of the obtained composites detected that samples that contained a bimodal ceramic reinforcement of fine SiC and coarse Al ₂ O ₃ particles, the strength and hardness were the best.	[60]
Equal channel Angular pressing method			
AA6060	ECAP	Implemented ECAP in the direct recycling of aluminium waste for cars. The efficiency of aluminium degreasing methods alloy AA6060 turnings was also investigated. The study suggested that the ECAP technique was suitable for aluminium alloy chips.	[61,62]
Friction stir casting			
Al 7075	Stir casting	The findings found that mechanical properties were greatly enhanced, such as superior wear and corrosion resistance and low thermal expansion coefficient relative to conventional base alloys. Albeit the improved properties, the process was deficient in maximising the usage of materials, and energy demand were relatively high compared to direct recycling. The study showed that AA 7xxx alloys are recyclable, and this information was relevant for selecting the AA7075 alloy.	[19]
Friction extrusion			
AA2024 AA7075	Friction stir welding	The effect of base metal (BM) locations on the corrosion actions of dissimilarly welded friction stir welded 2024-T351 to 7075-T651 aluminium alloy joints in an EXCO solution was reported. The possible usage of the AA7075-ZrO ₃ composite reported in the automobile industry required that the composite be weldable.	[63]
Forging			
AA6061-T6	Direct hot forging	Direct hot forging was carried out on AA6061-T6 chips and eliminated the phases of cold-compact and pre-heating. The RSM (response surface methodology) was used to optimise the process.	[64,65]

A new approach to the design of ECAP has been created for the current research. The system was constructed from a hydraulic machine with a pressing limit of 50 tons, and ECAP related accessories, such as a data logger, were connected with thermocouples that were inserted in the 8 ECAP holes to obtain the distributed temperature along with the system [66]. The proposed concept was deemed to be adequate for the hot ECAP extrusion die used in producing sufficiently high pressure and strain for the consolidation of chips.

5.3. Experimental Factors Influencing the ECAP Method

5.3.1. Inner Angle

The inner angle Φ is one crucial factor that is required to obtain an improved strain of the AMMC material. A previous study suggested that the inner angle should be selected between 90° and 120°, with the analysis of finite element analysis demonstrating that the microstructure of the composite material was affected by the inner angle [67]. An inner angle of 90° was reported to be the most significant angle and it effectively achieved ultra-fine-grained microstructure development [58]. The parameters that can be modified during ECAP include the processing routes, the consecutive numbers of passes, and the inner angle [58]. However, the above studies were relevant in providing information on the choice of the inner angle, the processing route, and the number of passes. However, the effect of the inner angle on the microstructure of the recycled aluminium alloy-based nanocomposite

(AA7075-ZrO₂) was not the main objective of the study. It was evident that this parameter may affect the properties of the new composite herein reported, hence the reason for the investigation of the microstructure after the ECAP operation on the composite.

5.3.2. Outer Angle

It is important to note the impact of the outer angle, Ψ on the extruded billet when using the ECAP, as it affects the strain of the AA7075-ZrO₂ nanocomposite. The outer angle (Ψ) was suggested to be 20° to obtain a well-homogenised product and delivered good grain refinement [68]. The average equivalent plastic strain that was obtained for nanocomposite was influenced by the angles that were used in the ECAP channel. Friction is an important factor in getting the punch load to extrude the billet. A previous study reported that the maximum strain was obtained when $\phi = 90^\circ$, $\psi = 15^\circ$, and $\mu = 0.3$ [58].

5.3.3. Pressing Speed

The pressing speed is a significant factor to be addressed in the ECAP process. A study investigating the effect of pressing force on the quality of products using ECAP suggested using a combination of the FEM software (Finite Element Method) and a comparative study with experimental work. It was found that the punch force during the experimental procedures and simulation had very close similarities and the same conditions [69].

The challenges of ductility, toughness, and durability of the die set used in ECAP were reducible when the temperature was low. This was possible through high straining during the processing of the composite material [70]. An experimental study showed less influence on the equilibrium state of ultra-fine grain that formed by the ECAP process when pure Al was pressed [56]. Suitable pressing speed choice and temperature are important in obtaining a high-quality, ultra-fine grain nanocomposite.

5.3.4. Pressing Force

The quality of the nanocomposite product is a function of the pressing force that is used in the ECAP die, and the force determines the microstructure and level of compactness, as the composite homogeneity is force-dependent among the other parameters. Previous studies have validated the pressing force using the FEM software while comparing the outcome with experimental work to the theory [71].

5.3.5. Pressing Temperature

The effect of temperature used during the ECAP process is of key consideration, as it affects the quality of the composite material. A study involving the fabrication of a composite material using a metallic powder of aluminium and steel suggested that the consolidation of powder metals be performed at room temperature. However, the higher the pressing temperature, the lower the tensile strength during the ECAP processing, and there was also an increase in the total elongation [72]. Besides, the importance of temperature is due to the reduction in high-angle boundaries and the transformation of the metal phase. Furthermore, it has also been reported that 15 min was used in heating the die to obtain the desired temperature of the furnace [55]. When the temperature was increased from 200 °C to 250 °C and 450 °C during the continuous ECAP process, there was a reduction in the grain size and microstructure [73]. When the temperature was reduced, more straining force was required for mitigating the challenges of ductility in the composite material and durability of the die set during the ECAP process [67]. It was evident from previous studies that the physical and mechanical properties of the current AA7075-ZrO₂ nanocomposite could be affected by temperature variation, among other experimental parameters, further emphasising the need for optimisation to obtain the best mechanical properties for industrial applications.

5.3.6. Processing Routes of ECAP

In principle, the routes that were used for the deformation of the billet followed the process of turning the billets over 0° , 90° , and 180° as the material undergoes each ECAP extrusion pass [74]. The procedure was repeated to attain a good distribution of the strain along the cross-section of the material. Generally, four leading handling routes are commonly used to investigate the microstructural changes of materials through ECAP [66].

1. Route A: The sample was pressed in a single direction without rotation. This point of entry at the beginning was maintained throughout the pressing operation.
2. Route BA: The sample was rotated at 90° alternatively, clockwise, or counterclockwise, with the material suggested to be exposed to pressing routes in two opposite directions when rotated at 90° .
3. Route BC: The sample was rotated 90° clockwise between the passes.
4. Route C: The sample was rotated with an angle of 180° . This route was proposed to expose the material to pressing in all directions during the operation. The implication was that the composite material would show uniform homogeneity while using this route, as the crystalline arrangement is affected in all directions.

The routes used during the ECAP process affect the microstructure, compression, mechanical properties, deformation behaviour, and strain distribution of the light metal workpiece [18], as the flow of the bulk material is informed by the direction of pressing.

6. Aluminium Metal Matrix Composite

Metal matrix composites (MMCs) are metal-based, and composites made from aluminium alloys have advantages when compared to steel-made ones. This is due to the unique features of aluminium alloys, including being lightweight and having high specific strength. In addition, the alloy has strong corrosion resistance, and it is easily extruded because it is ductile and malleable. Alloys of aluminium 7075 are being explored for diverse applications at the premises that are mentioned above, such as structural components requiring thin walls and the capacity to bear a load. Some building structures have been constructed using this alloy, including bridge floors, offshore stages, and large-span spatial lattice structures. Examples of areas of application include the Dome of Discovery in the United Kingdom, the Shanghai International Gymnasium in China, and the Shanghai Science and Technology Museum in the United States, which were all fabricated using aluminium alloys [75].

The application areas of MMCs have spanned structural components, such as engineering systems, the automotive, and aerospace industries. MMCs were reported to possess some strength improvement mechanisms when compared to conventional materials and continuously reinforced composites [6]. MMCs formed using aluminium as the matrix with particulate as reinforcement materials have been reported to be used for key automotive applications. For example, components of the engine, such as piston cylinder, parts of the brake system, such as discs/drums in railway vehicles, and aerospace are application areas of MMCs [76]. Aluminium alloys are extensively reinforced using ceramic particles, such as SiC and Al_2O_3 . Other reinforcement materials have now been suggested as alternatives, including a new group of particles, like ZrO_2 and ZrB_2 , with the end products displaying encouraging results [47].

Heat treatment improves the mechanical properties of this alloy, as the formation of secondary phases and homogeneous distribution of fine precipitates during heat treatment improve the properties [76]. The pursuit of improved reliability in applications, being cheaper and affordable, and enhanced material quality were the reasons for designing materials from monolithic to composite materials [19]. The main alloy element in the 7xxx series alloy is Zn; hence, this alloy is also known as an aluminium–zinc alloy. The wt.% of zinc is between 5.1% and 6.1%, as presented in the chemical composition that is shown in Table 4. This alloy was initially designed to fabricate airframes that were used by the Imperial Japanese Navy [77].

Table 4. Chemical composition of the AA7075 aluminium in wt.%.

Element	Percent (wt.%)	Atomic Mass (u)
Si	0.1	27.97
Fe	0.19	55.84
Cu	1.53	63.54
Mg	2.55	24.3
Zn	5.89	65.38
Mn	0.07	54.93
Cr	0.18	51.99
Ni	0.0058	58.69
Ti	0.024	47.86
Al	Bal	26.98

The mechanical, tribological properties and corrosion behaviour of AA-7075 metal matrix composites (AMMCs) are affected by the addition of desirable reinforcements from the foregoing due to the microstructure and composition of alloy elements changing with the addition of reinforcements. Earlier investigations have shown that reinforcements may be particulates, micro, or nanoparticles of SiC, Al₂O₃, Gr, TiO₂, bagasse ash, and ZrO₂ [47]. These reinforcements were reported to be partly responsible for the significant improvement that was observed in the properties. Table 5 presents the typical physical, mechanical, thermal, and electrical properties of AA7075 [78,79].

Table 5. The properties of AA7075.

Physical Properties	Value
Density (g/cc)	2.81
Melting Point (°C)	660
Mechanical Properties	Value
Hardness (BHN)	150
Ultimate Tensile Strength (MPa)	228
Yield strength (MPa)	103
Modulus of Elasticity (GPa)	70–80
Poisson's ratio	0.33
Thermal Properties	Value
Melting Temperature (T _m)	477 °C (891 °F)
Thermal conductivity (k)	196 W/m × K
Linear thermal expansion coefficient (α)	2.36 × 10 ^{−5} K ^{−1}
Specific heat capacity (c)	714.8 J/kg × K
Electrical Properties	Value
Volume resistivity (ρ)	51.5 nOhm × m

Despite the good mechanical properties that are presented above, the addition of composite particulates to the AA7075 was reported to improve the properties and widen the application area of the alloy, with the rationale being the level of reinforcement provided to the alloy chips with the addition of particulates or nanocomposite additives. With improved compressive behaviour and tensile strength in terms of mechanical properties, the composite material was formed using aluminium alloy as matrix material. Changes in the tribological properties were also observed when the matrix or the particulate used as filler material phase was changed [19]. When fabricating AMMC materials, it was found that the chemical composition was different as a reflection of the method that was adopted for combining or mixing the composite material during sinter face and separating them. For instance, the composite material can be formed with more than two macro, micro, or nano-constituents [80].

Unreinforced materials may have less strength than reinforced materials. In contrast, the latter has improved stiffness, high specific modulus, low thermal expansion coefficient, lightweight, high thermal conductivity, increased wear resistance, tailored electrical properties, and improved damping capabilities [80]. Metal matrix composites are among the fast-developing group of materials due to their unique combination of properties that guarantee low weight, improved strength, improved wear, corrosion resistance, and comparatively sensible plasticity. This mix of properties may result from the mixture of two kinds of materials with entirely different properties. Metal as the ductile matrix was reinforced with oxides and carbides, with Al_2O_3 , SiC, and ZrO_2 being the most favoured reinforcement materials. Reducing particle size considerably benefits the overall mechanical properties. Consequently, the current trends in MMC production primarily embrace the use of nanoparticles, thus creating various types of nanocomposites [74]. However, this study was conducted to obtain optimum mechanical properties using nanocomposites. The rationale for using nanocomposites was based on improved mechanical properties instead of macro or micro particulates. There are many materials used to reinforce aluminium alloys, with carbides (e.g., TiC), borides (TiB_2 and ZrB_2) and oxides (ZrO_2 , Al_2O_3 , and SiO_2) on the list of superior reinforcement materials, and these particulates have an equally high melting point and good thermal stability [74]. Titanium diboride (TiB_2) is incredibly enticing due to its high elastic modulus and hardness.

7. Zirconium Oxide ZrO_2 Reinforces the Aluminium Matrix Composite

Technological advancement has demonstrated the need to develop innovative materials that can be deployed for structural applications in the aerospace, automotive, electronics, energy, and manufacturing sectors [81]. Recently, advances in nanoscale technology have made the use of nano-sized particles possible in all spheres of life. The objective was to assess the feasibility of fabricating the AA7075- ZrO_2 nanocomposite utilising a combination of SPD processes. The crystal structure of zirconia is different with temperature changes; hence, it is a polymorphic material with a monoclinic phase, a tetragonal phase, and a cubic phase [82]. The monoclinic structure of ZrO_2 is stable at moderate or room temperatures, due to the formation of a solid covalent bond (Zr–O) and it forms the monoclinic ZrO_2 [83].

ZrO_2 has favourable mechanical and electrical behaviour, good wear resistance and corrosion resistance, and a wide bandgap. The material is thermally stable with high dielectric constants and chemical inertness [84]. The properties that are mentioned above suggest that the formation of the AA7075- ZrO_2 nanocomposite with high mechanical properties may find applications in the transportation industry. Other areas of application of ZrO_2 include solid fuel cells, catalytic agents with durability as a coating material, and gas sensors [85].

The literature lacks reports where zirconium has been used as a reinforcing material in aluminium matrix composites, with limited studies reporting the use of a small weight fraction of zircon oxide. For instance, 2.5 wt.%, 5 wt.%, and 7.5 wt.% volume fraction were used [86]. On the other hand, reduced wt.% to 1.0, 1.5, 2.0 respectively [85], while utilised 2.0, 2.5, 3.0, and 3.5 wt.%, respectively, with both studies being performed using the stir casting process [87] prepared MMCs by strengthening zirconium oxide nanoparticles in aluminium alloy Al7075, using a stir casting technique with a percentage of volume fraction of reinforced particles as two factors of 5% and 10%. Optimal ultimate tensile strength (UTS) was observed at 95% Al 7075/5% ZrO_2 with 135 N/mm² [88]. However, for 90% Al 7075, the highest hardness was 104 BHN at 10 wt.% ZrO_2 . The microstructural analysis demonstrated a uniform distribution of ZrO_2 particles. The mechanical properties of the AA6061 alloy were enhanced following the reinforcement of the alloy with zirconium dioxide. The wt.% zirconium varied at 0 wt.%, 2.5 wt.%, 5 wt.%, and 7.5 wt.%, respectively, while using the stir casting route and the reinforcement enhanced tensile strength and hardness of the MMC [89].

In an independent study, a new material of A356 aluminium alloy was fabricated by reinforcing it with 0.75%, 1.5%, and 2.5% of Al_2ZrO_5 nanoparticles through the stir casting

method. The 1.5 wt.% composite showed improved compressive strength and hardness values with values of 900 MPa and BHN 61, respectively [90].

On the other hand, AMMCs were fabricated using Molten Al356.1 reinforced with nano-sized zirconium particles with different proportions at 1.0 wt.%, 1.5 wt.%, and 2.0 wt.% through stir casting at a temperature of 750 °C [85]. Thixoforming (semi-solid processing) was obtained for 7075 aluminium alloy through the addition of modifying agents. The use of 0.5 wt.% of scandium and zirconium led to an increase in the average tensile strength and hardness [91]. Prasad and Mallikarjuna [37] investigated the tribological properties of aluminium alloy and demonstrated that the uniform distribution of particles that were integrated with B₄C and ZrO₂ improved the wettability and porosity of the composite material. Fabrication was carried out using the stir casting route with varying the weight fraction of ceramic particles at 1%, 2%, and 3%, respectively. The results reveal that the wear resistance improved with an increase in B₄C and ZrO₂ reinforcement in the wear test [37]. The planetary ball mill, horizontal attritor mill, and shaker mill were employed to process the composite with two different contents of ZrO₂ 2 wt.% and 5 wt.% nanoparticles to analyse the features of each mill that can affect the composite synthesis during processing [92].

A study investigating the effect of the addition of ZrO₂ content and temperature used during casting on the mechanical structures and behaviour of fractures of A356 Al/ZrO₂ composites was conducted by [93]. The AA 6061 was used as the base material, while different weight percentages of Silicon Carbide (SiC) were used as reinforcements at 2 wt.%, 4 wt.%, and 6 wt.%, respectively, and zirconium dioxide (ZrO₂) was fixed at 3.0 wt.%. In fabricating the AHMMCs, the stir casting method was adopted using a stirrer speed at 350 rpm and then held for 5 min [93]. Similarly, when there was an increased weight percentage of the reinforcing material, the impact of energy also improved. It was observed that the formation of hardening reinforcement particles was responsible for the properties (Table 6) [94].

Table 6. Volume fraction % of ZrO₂ reinforced particles and nanoparticles.

MMCs	Volume Fraction % ZrO ₂	Technique	Refs.
Al ₂ O ₃ /ZrO ₃	5%, 10%, 15%, 20%	Surface modification with aqueous solutions	[95]
Al7075/ZrO ₃ /Fly Ash	0%, 3% ZrO ₂ , 6% fly ash 4th 3% ZrO ₂ , 6% fly ash	Stir casting	[96]
Al/ZrO ₂	5–80%	Powder technology	[97]
Al/ZrO ₂	1%, 2%, 3%	Liquid Routing	[98]
Al/ZrO ₂ /Al ₂ O ₃ /TiO ₂	0–5%	Stir casting method	[99]
Al6061/ZrO ₂ /SiC	2%, 4%, 6% SiC 3% ZrO ₂	Stir casting method	[94]
Al6061/ZrO ₂	2.5%, 5%, 7.5%	Stir casting	[89]
A356/Al ₂ ZrO ₅	0.75%, 1.5%, 2.5% Al ₂ ZrO ₅ nanoparticle	Stir casting	[90]
Al356/ZrO ₂	1.0%, 1.5%, 2.0% nanoparticle	Stir casting	[85]
Al7075/Sc/ZrO ₂	0.5% Sc, 0.5% ZrO ₂	Semi-solid processing	[91]
Al/B ₄ C/ZrO ₂	1%, 2%, 3% B ₄ C/ZrO ₂	Stir casting	[37]
Al7075/ZrO ₂	2%, 5% ZrO ₂ nanoparticles	Three balls mills	[92]
A356/ZrO ₂	5%, 10%, 15% ZrO ₂	Stir casting	[93]

Based on earlier studies, zircon is a hybrid reinforced particle that has superior material matrix characteristics, such as (i) great mechanical and physical abilities, (ii) high fracture toughness, (iii) excellent resistance to corrosion, (iv) excellent wear resistance, and (v) excellent heat resistance.

8. Mechanical Properties

The material's mechanical properties play a significant role in determining the area of applying the material and the appropriate combination of the processing parameter. Strength, ductility, stiffness, resistance to impact, and fracture toughness are the most important mechanical properties to be considered. In the current research, the tensile

properties and microhardness of the aluminium composite were used as parameters for evaluating the product through hot extrusion and ECAP process.

8.1. Tensile Strength

Maximum tensile strength refers to a material or structure's ability to withstand a charge that tends to elongate. The attractive high strength to weight ratio observed in the AA7075 has earned a place in applying construction materials. The lightweight made the material suitable for rock climbing equipment and bicycle components. Although superior properties were stated above, there are also issues limiting the application areas of the alloy [47]. A tensile test was performed in previous studies to determine the aluminium and plastic flow stress of aluminium 7075. A standard test bar was used, with an inner diameter D of 6 mm and a length of the narrow segment (L) of 30 mm. The obtained data were converted into a true stress-true strain diagram, and the flow stress was then measured, as seen in [41]. The DEFORM 3D finite element software was utilised to conduct the theoretical investigation in order to simulate the stress-strain relationship. The aim was to demonstrate that the material behaved as aimed. During the simulation, the central axis of the symmetry model was used to improve the speed of the simulation. The parameters were collected for the AA7075 alloy and used as the plastic flow stress values during the tensile test. These parameters substituted the data for the 7075 alloys in the database [99].

Table 7 shows the development of TS (Tensile Strength) results from different types of reinforced materials. The nanomaterials composites in the matrix increased the material strength.

Table 7. The tensile strengths of different samples.

Material	TS (MPa)
TiC and TiB ₂ reinforced AA7075 hybrid composite	125
Sic-6%, ZrO ₂ -3% reinforced AA7075	131.15
Cenosphere reinforced AA7075	160

8.2. Microhardness

Hardness is common mechanical research that is used to estimate the mechanical strength of a material. The hardness value that was obtained from the hardness test reflects the material's resistance to plastic deformation. A material with higher hardness values was associated with greater resistance to deformation [100]. Microhardness is directly influenced by the temperature effect and ECAP number of passes. Increasing the temperature from 350 °C to 500 °C caused the solid-state light metal recycling to be decreased due to the increase in recovery and grain size. Higher hardness values were obtained because of the plastic strain during compaction [101,102].

8.3. Compressive Strength Test

Compressive strength is the ability of a material to retain load or withstand burden until it fails. This is the opposite of the material's tensile strength, which is its ability to withstand elongated loads that are applied to one end of the material. In the simplest sense, compressive strength is the ability of a material to resist compression. Knowing that the compression test is where the load is applied and the specimen is squeezed between two plates, it was observed that the compressive test caused the cross-section to increase [103].

9. Conclusions and Prospective

In summary, the previous literature was explored to examine studies on reinforcing nanoparticles to enhance the mechanical and physical properties of composite aluminium-based materials. ZrO₂ nanoparticles have good properties, such as low thermal expansion coefficient, good re-resistance to thermal shock, high melting point, and low thermal conductivity. AA7075 is considered to be a high-strength alloy, since its yield strength is

over 500 MPa in optimal ageing conditions. The alloy also has good corrosion resistance, as well as good electrical and thermal conductivity among the Al alloy family.

Hot extrusion is an innovative process in which low energy and less labour are required, and the mechanical properties of the composite are improved. The heat treatment that was conducted after hot extrusion improves the tribological and mechanical properties and the high bonding quality of Al nanocomposite.

The ECAP is considered to be the most recent on SPD techniques producing bulk and light recycled metal chips, such as aluminium characterised porosity-free and ultra-fine-grained materials.

An extrusion preceding the ECAP method was used to produce miniaturising Al specimens, and the thermal stability was reported to be good. It was also evident from the literature that limited studies were carried out using AA7075 alloy as AMMC and ZrO₂ as a nano-articulate of directly recycled alloy chips. The need for optimisation was due to the variations in the nanocomposite fabrication parameters, which makes it challenging to obtain the best mechanical and physical properties.

For decades, inefficient waste management raised many global concerns regarding the way that we preserve energy and the apparent underestimation of the disposals' environmental impact. All of that leads to the revolution of waste recycling and reusing and encourage more researchers and companies to develop energy-efficient approaches to fabricating recycled metals. Much of the newly emerging research discusses multicomponent products' properties, such as AA7075 incorporated ZrO₂ belonging to high-entropy alloys with high-performance properties using different manufacturing techniques. Thus, reducing the metal waste and developing green manufacturing processes decreases greenhouse gas emissions and lower energy usage. On the other hand, the increasing attention to the superior properties of ultrafine-grained metals with a 1 µm average grain size put them as strong upfront candidates for their high structural stability and controllability and the variety of applications, especially in lightweight-needed properties, such as aircraft engines.

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