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A REVIEW ON THE EFFECTS OF THE REDUCTION RATIO AND THE DIE ANGLE ON THE PROPERTIES OF EXTRUDED Al-Zn-Mg ALLOY

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Abstract

Extrusion is a widely used technique in processing Al-Zn-Mg alloys due to its efficiency, cost-effectiveness, and ability to enhance mechanical properties. This study examines the effects of two critical extrusion parameters namely, reduction ratio and die angle on the mechanical and microstructural behavior of these alloys. Studies show that increasing the reduction ratio from 8:1 to 24:1 significantly refines grains, boosts tensile strength by up to 30%, and increases hardness through enhanced plastic deformation and dynamic recrystallization. However, excessively high ratios may cause tool wear and reduced ductility. Smaller die angles of 15°–30° yield more uniform deformation and finer grains, improving strength and hardness. Die angles greater than 60° increase extrusion pressure, decrease stability, and may impair performance. Optimal results of tensile strength exceeding 400 MPa and elongation over 10% are achieved at die angles of 30°–45° and reduction ratios of 16:1–20:1. This review provides a novel synthesis of parameter-property relationships, offering valuable insights for optimizing extrusion conditions to achieve superior mechanical properties in Al-Zn-Mg alloys.

Keywords: *Extrusion, Reduction ratio, Die angle, Al-Zn-Mg alloy, Mechanical Properties.*

Introduction

Extrusion can be defined as a severe plastic deformation technique, whereby a metal billet under high pressure is pressed into a die orifice, thus decreasing its cross-section. This procedure, used in materials processing, is like squeezing toothpaste from a tube, and the term extrusion is typically used to refer to both the procedure and the outcome. Meanwhile, the extruded product forms a continuous rod with the same cross-section as the die orifice [1, 2]. During the extrusion process, a heated billet is pushed through a die at a temperature of between 450°C–500°C, where a low flow stress allows for significant deformation under shear and compressive forces, without tearing. After extrusion is complete, the remaining billet section is trimmed [3].

Extrusion technology, a key metallurgical processing technique since the 19th century, has gained prominence during World War II to produce aeronautical components. Its continued relevance in recent advancement lies in its ability to create complex geometries with high design and functional flexibility [4-8]. Aluminium, especially in the 6xxx alloy series, is widely used in industries, such as construction, transportation, and structural engineering for its strength, corrosion resistance, and workability, with the extruded profiles, offering versatility and design flexibility. However, the extrusion process is complex, and it is influenced by multiple variables

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across different stages that require careful control to ensure product quality, conformity, and cost-effectiveness, while minimizing material waste [9, 10].

The reduction ratio and the die angle significantly influence the mechanical properties and microstructural evolution of extruded Al-Zn-Mg alloys. High reduction ratios and small die angles promote better strength and uniformity by enhancing plastic deformation and grain refinement, while low ratios and large angles can lead to defects and weak structures. Therefore, the optimization of both parameters is crucial for the achievement of desirable strength, ductility, and structural integrity in Al-Zn-Mg extrusions [11]. This study is focused on the systematic review and comparative analysis of how reduction ratio and die angle collectively influence the microstructure and mechanical performance of extruded Al-Zn-Mg alloys, providing optimized parameter ranges for enhanced material properties.

Types and Advantages of the Extrusion Process

The extrusion process can be grouped into two major types, namely: direct and indirect extrusions (Fig. 1). The direction of the punch movement and the metal flow are the same in the direct extrusion and extrusion of the metal through the die hole is carried out until very little sample is left. The indirect extrusion process is like the direct process, except that the direction of metal flow is opposed to the ram travel. In here, at the billet-container interface, there is no relative motion other than that of the die, as it approaches the billet.

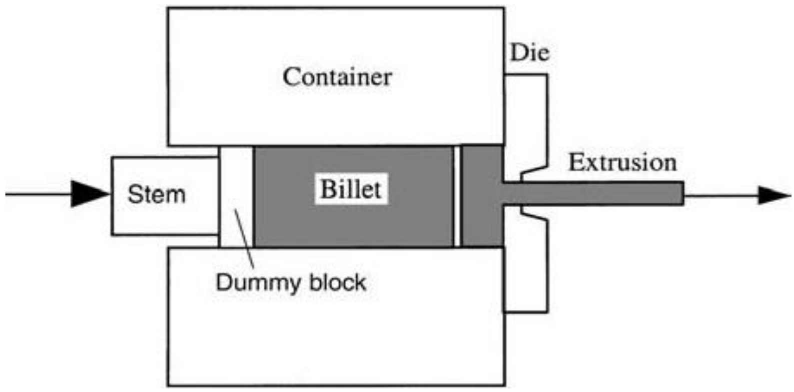
Consequently, when compared to direct extrusion, the force needed for extrusion is smaller and the frictional forces are reduced. One end of the container is a closed plate, while the other is a hollow ram that holds a die. The tubes are normally extruded *via* this method [3]. The extrusion process has a major advantage over other forming techniques in that it can produce extremely complicated cross-sections, and it is effective with brittle materials [12]. Because the material only experiences shear and compressive stresses, it produces finished products with exceptional surface finishes [13].

The quality of an extruded product is influenced by several factors, including geometric accuracy, chemical composition, surface finish, microstructural uniformity, and consistent mechanical properties along the product's length and cross-section. Contaminants, such as oxides, dust, or lubricants at the billet-to-billet interface can create weak welding zones that necessitate material discharge. Inadequate control of extrusion parameters may lead to defects, which often, stem from poor quality billets, tooling issues, extrusion-induced faults, or post-processing failures.

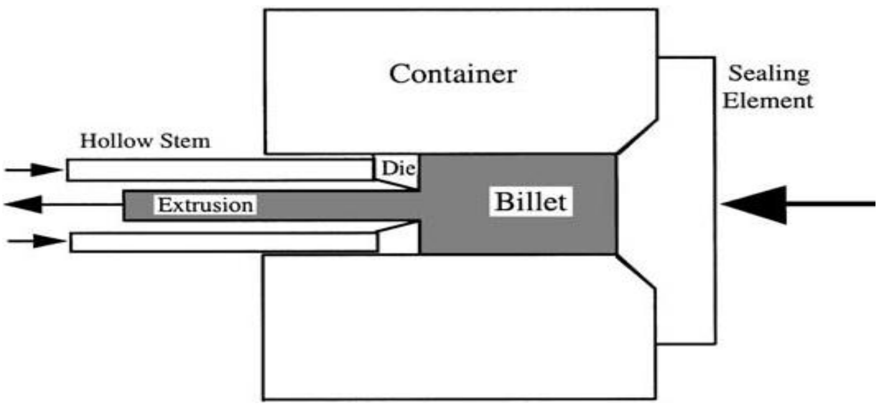
Strain concentrations are common at the longitudinal and transverse welds and back-end regions, sometimes causing macro bores due to irregular metal flow. Depending on conditions/parameters, such as extrusion ratio, die angle, deformation zone height, friction, and material behavior, defects, such as axial holes, fir-tree cracking, and chevron cracks may occur. Surface flaws, such as die lines, blisters, cracks, and weld lines, highlighted by Carvalho [14], result in increased production costs, delivery delays, and high scrap rates.

Performance Requirements of Die Materials in Extrusion of Al-Zn-Mg Alloy

Die materials play a critical role in the extrusion of Al-Zn-Mg alloys, since they directly influence heat transfer, wear resistance, surface finish, dimensional accuracy, and tool longevity. The selection of appropriate die materials is essential for maintaining the integrity of the extruded product and ensuring consistent mechanical properties. Die materials must withstand the high temperatures, generated during the extrusion of Al-Zn-Mg alloys, which can exceed 400°C. When compared to mild steels, materials with high thermal conductivity, such as fir tree cracking hot-work tool steels (e.g., the H13), are commonly used because they allow for efficient heat dissipation, reducing thermal fatigue and the risk of die failure [15]. These steels retain their strength and hardness at elevated temperatures, which is critical in maintaining the die shape under prolonged thermal cycling. Al-Zn-Mg alloys contain hard intermetallic particles (e.g., $MgZn_2$), which can be abrasive to the die. Die materials must exhibit excellent wear resistance to prevent degradation over time. Hardened tool steels and carbide materials are often used in applications that require high durability, especially for high-volume or high-pressure extrusion [16].



a)



b)

Fig. 1. Types of extrusion: a) direct extrusion; b) indirect extrusion

The interaction between the die surface and the billet can significantly affect the surface quality of extruded products. Die materials that allow polished or coated surfaces (such as nitrided H13 or ceramic-coated dies) can reduce friction and improve the flow of metal, which is essential for avoiding surface defects, such as die lines and tearing. Low friction also contributes to reduced extrusion pressure and improved material flow uniformity [17]. Die materials must maintain dimensional stability during repeated thermal cycles. High toughness and resistance to thermal fatigue are essential to prevent cracking and distortion. Advanced die materials, e.g., powder metallurgy (PM) tool steels, have exhibited better fatigue resistance and stability, especially under high reduction ratios or complex die geometries [18]. Some die materials perform better when combined with specific lubricants or surface coatings (e.g., TiN or CrN coatings). These coatings enhance the nitrided H13 die life and reduce aluminum adhesion (die soldering), which is common in the Al-Zn-Mg alloy extrusion due to their chemical reactivity at high temperatures [19].

Tables 1 and 2 below show the mild and tool steels chemical compositions, respectively which were determined using Optical Emission Spectroscopy (OES), a widely employed technique for accurate elemental analysis of metallic materials. The analysis was conducted using a Spark-OES analyzer, which provides rapid, non-destructive, and reliable determination of both major and minor elements in solid metallic samples [20]. Both the mild and tool steel used as die materials are usually machined to form a round end section having entrant angles of: 15°, 30°, 45°, 60°,75° and 90°, as shown in Fig. 2. Annealing process is carried out on dies made of mild steel by heating them to a temperature of 850°C and holding them at this temperature for 3 hours. The tool steel dies are normalized by heating them to a temperature of 750°C and holding them for 3 hours and then, air cooled. The ram and form tool, which are usually composed of mild steel are heated to 850°C, held for 3 hours and then quenched in water. By carrying out this procedure, the hardness and strength of the products are increased to avoid deformation and wear during extrusion [20].

Table 1. Mild steel spectrophotometer analysis

Element	Composition (%)
C	0.119
Si	0.289
S	0.010
P	0.010
Mn	0.503
Ni	0.021
Cr	0.043
Mo	0.005
V	0.007
Cu	0.031

Table 2. Tool steel spectrophotometer analysis

Element	Composition (%)
C	0.198
Si	0.440
S	0.010
P	0.009
Mn	0.139
Ni	0.017
Cr	0.006
Mo	0.005

Effect of Casting Parameters on the Quality of Al-Zn-Mg Alloys

The casting process of Al-Zn-Mg alloys is a crucial step in shaping and preparing the alloy for subsequent forming or extrusion operations. These alloys are typically cast by using techniques, such as gravity die casting, high-pressure die casting, or semi-continuous casting, depending on the application requirements. During casting, careful controls of the cooling rates and the chemical composition is essential to minimize common defects, such as porosity, hot tearing, and segregation. These defects are particularly pronounced in the high-strength Al-Zn-Mg systems due to their wide solidification range and sensitivity to impurities [21].

The presence of alloying elements, such as Zn and Mg, enhances the mechanical properties through precipitation hardening, but also increases the risk of solidification-related issues, if not managed properly [22]. Proper degassing and melt treatment techniques, such as the Argon purging and grain refinement (using Ti-B-based master alloys), are employed to improve the casting quality [23]. Additionally, advancements in directional solidification and rapid solidification technologies have further improved the microstructure uniformity and reduced the formation of coarse intermetallic phases, thereby enhancing the downstream workability and final properties of the alloy [24]. Table 3 shows the compositional analysis of cast Al-Zn-Mg alloy which was determined using Optical

Emission Spectrometry (OES), with the aid of spark emission spectroscopy (Spark-OES) analyzer. This technique is widely employed for quantitative analysis of metallic materials due to its high sensitivity, precision, and ability to simultaneously detect a wide range of elements, including trace constituents [25].

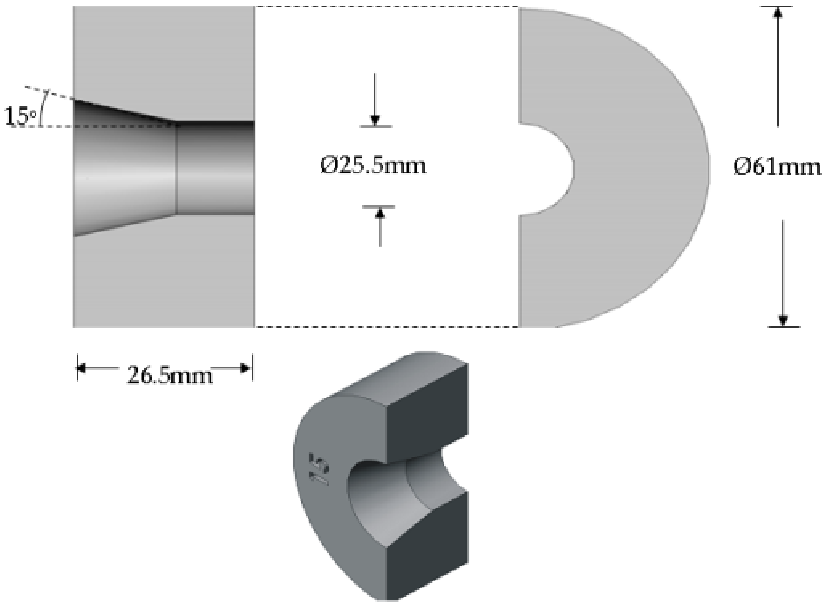


Figure 2. Extrusion die of isometric view with a 15° entrant angle.

Table 3. Compositional analysis of Al-Mg-Zn alloy

Element	Composition (%)
Si	0.82
Fe	0.16
Cu	0.17
Mn	0.18
Mg	2.66
Cr	0.0194
Ni	0.102
Zn	5.79
B	0.0014
Be	0.00046
Bi	0.0035
Ca	0.0012
Co	0.00061
Na	0.00014
Pb	0.0505
Sn	0.0292
Zr	0.0029
Al	88.20

Evaluation of Extrusion Process Parameters

Extrusion/reduction ratio

A metal flowing pattern in extrusion is significantly affected by the die design, friction requirements at the interfacial surface of the die and the billet, as well as the temperature differential around the billet [26]. The reduction ratio, R, is among the major requirements that characterize an extrusion process, as shown in Eq. 1 [26]:

$$R = \frac{A_i}{A_f} = \frac{D_i^2}{D_f^2} \tag{1}$$

where A_i is the initial cross-sectional area, A_f is the final cross-sectional area, D_i is the initial diameter, and D_f is the final diameter after the extrusion of the billet. The strength characteristics of the process is affected by the reduction ratio, as well as the deformation level and the flow characteristics of the material that is being extruded. The extrusion force increases in tandem with increase in the reduction ratio, thereby increasing the pressure on the tools, which resulted in wear [12].

Bajimaya [27], found that the metal flow during extrusion is governed by multiple factors, including the billet and the container temperatures, the extrusion pressure, speed, billet size, and the extrusion ratio (ER). Although finite element models aid in theoretical analysis, they lack the realism for a direct application in manufacturing systems. Peris [28] further observed that the ER directly affects the temperature rise due to friction-induced deformation, while high ER led to increased extrusion speed and acceleration time. Xu et al., [29] investigated an Al-6.3Cu-0.48Mg-0.4Ag alloy and found that increasing the ER reduced the fibrous microstructure size and enhanced the strength of the resulting alloy, while its elongation initially increased and later decreased.

Yang et al., [30] reported an inverse relationship between the ER and the solid solution temperature in a spray-formed 7075 aluminium alloy. Lu et al., [31] observed that the recrystallized grains in an AZ31-xCaO alloy became more uniformly distributed with higher ER. Similarly, Wang et al., [32] observed that the ER is directly proportional to the quantity of the second phases and inversely proportional to the grain size in Mg–Zn–Y alloys. Additionally, Li [33], Adachi [34], and Dong et al., [35] confirmed the fact that ER significantly affected the microstructure and properties of Al–Zn–Mg–Cu alloys. Hou [36] and Lee et al., [37] also explored similar effects in magnesium alloys.

Extrusion pressure

Extrusion pressure is influenced by the die design elements, including the punch geometry (indirect extrusion) and the die entrance angle (direct extrusion). Eq. 2 to Eq. 5 were derived by the Bethlehem Steel Company to determine the extrusion pressure [38].

For the direct extrusion:

$$P_f = 0.5\left[\sigma_{ys} + K(lnR)^n\right]\left(a_f + b_f lnR\right)\left(e^{4\mu Z}\right) \tag{2}$$

while for the backward extrusion:

$$P_b = 0.4\left[\sigma_{ys} + K(lnR)^n\right](a_b + b_b lnR)\left(\frac{R}{R-1}\right) \tag{3}$$

$$\text{where } a_f = 1.15\left(\frac{\alpha}{57.3sin^2\alpha} - cot\alpha\right) + 4\mu y \tag{4}$$

$$\text{and } b_f = 1.1 + \mu(1 + 0.5lnR)cot\alpha \tag{5}$$

where a_b = 0.28, b_b = 2.36, σ is the 0.2% of yield strength, K is the true flow strength, R is the reduction ratio, n is the strain hardening exponent, μ is the friction coefficient, Z is the ratio of the preform length to die diameter at the entrance, α is half the angle of the die, and y is the ratio of the length to diameter for the die land.

The extrusion pressure has always been determined by using nomograms and empirical formulae; however, a finite-element analysis has lately offered an alternative technique, particularly for complicated shapes, for the estimation of the extrusion pressure [38]. Eq. 6 provides the total extrusion pressure; P_T needed for a specific reduction ratio:

$$P_T = P_D + P_F + P_R \quad (6)$$

where P_D stands for the pressure needed for plastic deformation, P_F stands for the pressure needed to surmount the surface friction, and P_R stands for pressure that is needed to surmount a redundant or internal deformation work. The pressure required for the plastic deformation, P_D is expressed in a functional form, which is presented in Eq. 7, where $\bar{\sigma}$ and $\bar{\varepsilon}$ are the flow stress and strain, respectively.

$$P_D = f(\bar{\sigma}, \bar{\varepsilon}) \quad (7)$$

The flow stress, $\bar{\sigma}$, is defined in Eq. 8 as:

$$\bar{\sigma} = f(\bar{\varepsilon}, \dot{\varepsilon}, T) \quad (8)$$

where $\dot{\varepsilon}$ and T are the strain rate and the material temperature, respectively.

The functional form of pressure, P_F, needed to surmount the friction at the surface, at the wall of the container, dead-metal zone, and the die bearing friction, is provided in Eq. 9.

$$P_F = f(pr, m, m', m", D, L, L') \quad (9)$$

where p_r is the radial pressure, *m, m' and m"* are the frictional factors within the billet and the container wall, the dead-metal zone, and within the extruded material and the die land, respectively, while *D, L* and *L'* are the billet diameter, billet length, and the die land, respectively.

As seen in Eq. 10 below, the functional form of the pressure needed to counteract the redundant work, is provided, thus:

$$P_R = f(\bar{\sigma}, \alpha) \quad (10)$$

where the semi dead metal zone angle, α, is dependent on the reduction ratio.

For a direct extrusion, plastic deformation with respect to unit volume, is described by using the uniform deformation energy technique [39], as shown in Eq. 11, while the work involved is as shown in Eq. 12,

$$U_p = \bar{\sigma} \int d\varepsilon = \bar{\sigma} \int_{Ao}^{A_f} d\ lnA = \bar{\sigma} ln \frac{A_f}{A_o} = -\bar{\sigma} lnR \quad (11)$$

$$W = U_p V = V \bar{\sigma} lnR = \rho Al(force \times distance) \quad (12)$$

where U_p is the plastic work of deformation, V is the volume and $\bar{\sigma}$ is the effective compressive flow stress, hence from Eq. 12,

$$\rho = \frac{V}{AL} \bar{\sigma} lnR = \bar{\sigma} lnR \quad (13)$$

The actual extrusion pressure, p_e is presented in Eq. 14, thus:

$$p_e = \frac{p}{\eta} = \frac{\bar{\sigma}}{\eta} lnR \quad (14)$$

where ρ is the extrusion force and η stands for the efficiency of the system.

Fractional reduction in area, r

This is the difference between the billet's initial cross-sectional area, A_0, and the final A_f, cross-sectional area divided by the initial cross-sectional area A_0 [40]. It is expressed as shown in Eq. 15 to Eq. 18.

$$r = \frac{A_0 - A_f}{A_0} \quad (15)$$

$$r = 1 - \frac{A_f}{A_0} \quad (16)$$

$$\frac{A_f}{A_0} = 1 - r \quad (17)$$

$$\frac{A_0}{A_f} = \frac{1}{1-r} = R \quad (18)$$

where r is the fractional reduction area and R is the reduction ratio. The velocity, V at which a component is extruded, is as shown in Eq. 19, while the extrusion force, P is expressed as shown in Eq. 20, hence,

$$V = ram\ velocity \times R \quad (19)$$

$$P = kA_0 ln \frac{A_0}{A_f} \quad (20)$$

where k is a constant, an overall factor that takes into consideration, an inhomogeneous deformation, friction, and flow stress.

Extrusion temperature

The material-tool interface often has the highest temperature because of friction. If a thin plate is the material being deformed and the temperature gradient is ignored, then Eq. 21 provides the mean instantaneous temperature, T at the contacting points [39].

$$T = T_1 + (T_0 + T_1) exp\left(\frac{-ht}{\rho c \delta}\right) \quad (21)$$

where T_o and T_1 are the temperatures at the workpiece and at the die, respectively, while h, δ and t represent the coefficient of heat change within the material and the dies, the material thickness, and time, respectively. When deformation and friction are considered, due to rise in temperature, Eq. 22 provides the final mean temperature, $T_{m,}$ of the material, per time, t as:

$$T_m = T_d + T_f + T \quad (22)$$

where T_d and T_f are the temperatures for a frictionless deformation process, and for friction, respectively, while T is the average instantaneous temperature.

Influence of Extrusion Parameters and Reduction Ratio on Microstructure and Mechanical Properties

The extrusion pressure rises with increasing ram speed, while the billet cools more, when the extrusion speeds are low. Low extrusion speed has a strong effect on the billet cooling when the billet temperature is high. Thus, high-strength alloys that demand elevated extrusion temperatures require high extrusion speeds. For every alloy and billet size, it is advisable to use the "trial-and-error" scenario to determine the ideal extrusion temperature and speed. The reduction ratio or extrusion ratio increases with a rise in the extrusion temperature for certain extrusion pressure, and high reduction ratio was achieved with great extrusion pressure, for a given temperature [39].

The impact of the reduction ratio on the load and the die wear during extrusion process, was examined [12]. The findings revealed that the reduced values of reduction ratio did not require sufficient rigidity and the measure of the corresponding stresses, in the die corner region, were not significantly influenced by the extrusion ratio value. The upper bound assessment of extrusion at different die lands, was examined by Ajiboye and Adeyemi [40]. Their findings showed that the effect of the extrusion pressure, because of the die land at any given percentage reduction for shaped sections, theoretically increased with the die land lengths. Consequently, the impact of the reduction ratio was considered on the properties of the extruded products, as well as the strength and wear of the extrusion tooling [41]. For instance, in the extrusion of magnesium alloys, the reduction ratio influenced, considerably, the microstructure and hence, established the mechanical characteristics of the alloys produced [42, 43].

Yu et al., [44] examined how temperature as well as extrusion ratio affected the microstructural and mechanical characteristics of an extruded Mg-11.5Gd-4.5Y-(1Nd/1.5Zn)-0.3Zr alloy. In the same vein, Yang et al., [45] investigated how the extrusion temperature affected the microstructural and mechanical properties of a duplex Mg–Li–Al–Sr alloy. Their findings indicated the fact that the extrusion ratio, rather than the extrusion temperature and speed, had greater effect on the microstructural refinement of the magnesium alloys produced [46]. When the reduction ratio increased the microstructural refinement also increased and as a result, there were improvements in the yield and ultimate tensile strengths of the alloys produced [25, 47].

Wen et al., [48] and Feng et al., [49] examined how the reduction ratio affected the mechanical characteristics and the microstructures of a duplex-structured Mg–8Li–3Al–2Zn–0.5Y alloy and an extruded Mg–6Sn–2Zn–1Ca (TZX621) alloy, produced with a solid recycling technique. The microstructural as well as the mechanical characteristics of the extruded Mg-Sn-Zn-Ca (TZX621) alloy were also examined by Zhang et al., [50], in relation to the extrusion ratio. Results indicated that the TZX621 alloy's mechanical properties significantly improved as the extrusion ratio rose from 6 to 16.

Chen et al., [51] explored the effect of extrusion ratio on the microstructure and properties of Al–Zn–Mg–Cu alloy, produced *via* the Spray Conform (SC) processing. The study revealed that by increasing the extrusion ratio, significantly refined, the grain structure, improved the distribution of the second-phase particles, and enhanced the overall mechanical properties, including tensile strength and hardness of the alloy. High extrusion ratio values also contributed to a more uniform and denser microstructure with reduced porosity. These improvements were attributed to more intense plastic deformation and dynamic recrystallization during extrusion. Thus, the study confirmed the fact that the optimization of the extrusion ratio, is key to the tailoring of the performance of SC-processed Al–Zn–Mg–Cu alloys.

Although according to Tong et al., [52], there was no discernible influence of the reduction ratio on the mechanical, microstructural, and textural characteristics of an indirectly extruded Mg–Zn–Ca alloy. This resulted from the logical process, linking the texture decline and fine grain reinforcement. Guan et al., [53] also conducted a comprehensive investigation into how the extrusion ratio affected the Mg–Sm–Zn–Zr alloy's microstructure and tensile properties. According to their findings, the ductility of the extruded alloy increased as the reduction ratio increased, because of reduced texture and dislocation density. Table 4 below shows a summary of some findings on the reduction ratio, exhibited by extruded Al-Zn-Mg alloys.

Table 4. Summary of some findings on reduction ratio exhibited by extruded Al-Zn-Mg alloys

S/No	Author(s)	Die reduction ratio(s)	Findings	Remarks
1	Zhao et al. [54]	10:1 to 25:1	Increased reduction ratio of refined grains and reduced porosity. Tensile strength and hardness improved with high reduction ratio.	Optimal reduction ratio enhanced both strength and the microstructure.
2	Chen et al. [55]	12:1, 16:1, 20:1	High reduction ratio led to more uniform and fine grains. Yield strength increased with a reduction ratio, while elongation peaked but later dropped.	Reduction ratio significantly affected properties.
3	Wang et al. [56]	10:1, 15:1, 20:1	Grain size decreased with increasing reduction ratio. High reduction ratio enhanced strength but reduced ductility.	High reduction ratio is not always better for ductility.
4	Liu et al. [57]	8:1 to 24:1	Dynamic recrystallization was enhanced with high reduction ratios. Reduction ratio positively correlated with hardness and strength.	Reduction ratio crucial for tailoring performance.
5	Singh et al. [58]	5:1 to 20:1	High reduction ratio improved the second-phase distribution. Optimal reduction ratio balanced strength and ductility.	Reduction ratio optimization required for balanced a performance.

Effect of Die Angle on Mechanical and Microstructural Properties of Extruded Alloys

The geometrical features of an extrusion die influence the properties of extruded alloys. Studies have shown how the die angle affects the flow patterns, the extrusion pressures, and the quality of the extruded parts, for aluminum alloys. Onuh et al., [59] investigated how a die configuration as well as the extrusion speed affected the cold extrusion of lead/aluminum alloys. According to their findings, the specific extrusion pressure first dropped at a die angle of 90º before starting to increase as die angle increased. The lowest redundancy energy at a 90° die angle was the cause of this minimum extrusion pressure. Therefore, a complex-shaped section of a die design at an angle of 90º, was preferred to extend the die life.

Kumar et al., [60] examined how the die angle affected the characteristics of 6061 aluminum alloy reinforced with nano SiC during cold extrusion. Their findings revealed the fact that the extrusion load and hardness values decreased with increases in the die angle, while the surface roughness increased as the die angles increased. Radhi and Jabur [61] demonstrated that the billet's temperature distribution was significantly impacted by the die angle than was the case with the friction coefficient, since high die angle decreased the temperature distribution. Chaudhari et al., [62] also examined how the die angle affected both the hardness and the surface finish during cold extrusion of aluminum. They further verified the fact that the mean hardness values rose as die angle reduced and continued to rise as die angle was increased. Farayola et al., [63] investigated how the die entry angle affected the extruded lead alloy's mechanical characteristics. The study indicated that the die entry angles of 45°, 60°, and 75° were suitable for the attainment of a fine grain structure, with improvement in the material's strength, hardness and ductility.

An investigation into the thermal reaction of stress distribution analysis during various procedures, used for the extrusion of aluminum rods was evaluated by Kumar et al., [64]. Their findings give significant perceptions on the mechanical behavior and efficiency of aluminum rods. The angle of the die was considered a fundamental component in the shaping and forming operations, affecting the stress propagation inside the aluminum rod. Kumar et al., [3] examined how the die angle affected the extruded aluminum alloy reinforced with nano-SiC, comparing the outcomes to those of cold extruded Al6060 alloy. Die angles of 12°, 15°, and 25° were taken into consideration and from their findings, it was observed that the die angle increased with decreased extrusion force. While nano-SiC aluminum alloy demonstrated superior properties over Al6061 alloy, high hardness values and surface roughness were also observed as the die angles increased. This agrees with the report of Gbenebor et al., [65], who examined the influence of the die geometry on the deformation response and the energy-absorbing characteristics of 6063 Al-Mg-Si alloy.

By using various die entrance angles of: 15º, 30º, 45º, 60º, 75º and 90º, the impact of a steel die parameters and the microstructural assessment of AA 6063 aluminum alloy, extruded at ambient temperature was examined [20]. The extruded samples' microstructural examination, maximum extrusion pressure, elongation, hardness, and ram velocity were determined. The findings indicated the fact that as the die angle increased, the maximum extrusion pressure also increased as well as the hardness. Abdul-Jabbar and Abdullah, [66] investigated the impact of the die configuration on the properties of an AA7075 alloy, during a hot extrusion process by using die entry angles of 15°, 30° and 45°. Results showed that the extrusion load for the extruded samples, was higher at angle 30° and lower at angle 15°. For the hardness, the outer boundary of the samples subjected to the die configuration parameters, was very hard, while there were compression disparities of load in the samples.

Azeez et al., [67] examined how the extrusion of an Al6063 alloy was affected by the die angle, temperature, and number of passes. Their results showed that the die angle drastically, affected the load reduction, therefore, the load should be reduced, as much as possible to boost the market production. Table 5 below shows a summary of some findings on the reduction ratio, exhibited by the extruded Al-Zn-Mg alloys.

Table 5. Summary of some findings on reduction ratio exhibited by extruded Al-Zn-Mg alloys

S/No	Author(s)	Die reduction ratio(s)	Findings	Remarks
1	Li et al. [68]	30°, 45°, 60°	Refined grain structure at low die angles, increased dynamic recrystallization. High tensile strength and hardness at small angles, strength decreased at 60°.	Optimum strength observed at 45°.
2	Zhang et al. [69]	20°, 40°, 60°, 90°	Grain size increased with large die angles. Tensile strength and yield strength peaked at 40° but decreased beyond 40º.	Suggested 40° as the ideal angle for strength, ductility balance.
3	Afifi et al. [70]	15°, 30°, 45°	Grain refinement most effective at 15°. Highest hardness and tensile strength achieved at 30°	Trade-off between extrusion force and material properties.
4	Li et al. [71]	30°, 60°, 90°	Uniform microstructure at 30°, coarse grains observed at 90°. Strength and elongation dropped significantly at 90°	Observed an increase in the extrusion pressure with increasing die angle.
5	Wu et al. [72]	10°, 20°, 30°, 45°	Fine and equiaxed grains at lower angles, inhomogeneous structure above 30°. Best mechanical properties at 20°, deterioration at high angles	Demonstrated strong die angle influence on the dynamic recovery processes.

Recent Advances in Al-Zn-Mg Alloys for High Performance Extrusion Applications

Besides the reduction ratios and the die angles, researchers have also examined the properties of Al-Zn-Mg alloy using other parameters. Li et al., [74] investigated the effects of applying an electric pulse current during a hot extrusion process on the mechanical properties of Al-Zn-Mg alloys. The study found that the introduction of electric pulse enhanced significantly the extrudability and mechanical strength of the alloy. Specifically, the electric pulse improved the dynamic recrystallization behavior, resulting in a finer and more uniform grain structure. It also promoted a more homogeneous distribution of second-phase particles, which contributed to the increased yield strength and ultimate tensile strength of the extruded material. The researchers concluded that this technique is an effective method for refining microstructures and enhancing the overall performance of Al-Zn-Mg alloys during extrusion.

Guo et al., [75] explored the influence of Zn and Mg content on the crashworthiness of thin-walled square extrusions made from Al-Zn-Mg alloys. Their study revealed that increasing Zn and Mg contents, enhanced the energy absorption capacity and crash resistance of the extruded profiles. Specifically, higher alloying content led to stronger strain hardening and improved mechanical stability, under a dynamic impact, which are critical for applications in automotive crash components. However, they also noted that excessive Zn and Mg may lead to a trade-off with ductility. The research provided valuable insights for the optimization of Al-Zn-Mg alloy compositions for high-performance structural applications that require both strength and energy absorption.

Li et al., [76] investigated the evolution of microstructure and mechanical properties of Al-Zn-Mg-Cu alloy, through extrusion and subsequent heat treatment. Their findings showed that the extrusion process significantly refined the grains and improved the uniformity of the precipitates, thereby leading to enhanced mechanical strength. After applying an appropriate heat treatment, the alloy exhibited a marked increase in hardness and tensile strength due to the formation of fine, uniformly distributed precipitates, such as the η' phase. The study concluded that a well-controlled combination of extrusion and heat treatment, can effectively optimize the strength–ductility balance, thereby making the alloy suitable for high-performance structural applications.

Remsak et al., [77] examined the influence of Zn, Mg, and Cu contents on the microstructure and mechanical properties of extrusion-welded Al–Zn–Mg–Cu alloys. The study revealed the fact that by increasing the alloying elements, particularly Zn and Cu, led to a refined grain structure, enhanced precipitation hardening, and stronger weld seams. High Mg content contributed to increased strength but slightly reduced the product's ductility. The findings also showed that careful control of the alloy composition significantly improved the extrusion welding quality, with better mechanical performance in the welded zones due to a uniform microstructure and fine precipitate distributions. These results are critical for the optimization of extrusion-welded structural components in aerospace and automotive applications.

Yoo et al., [78] investigated the effects of strontium (Sr) addition on the microstructural, electrical, and mechanical properties of Al-Zn-Mg-Mn alloys. The study found that the inclusion of Sr led to a refinement of grain structure and the modification of the intermetallic compounds, hence, contributing to improved tensile strength and hardness. Additionally, the Sr addition slightly reduced the electrical conductivity of the material due to increased solute atoms and second-phase particles, but the mechanical property gained outweighed this drawback. Generally, the findings indicated that Sr is an effective alloying element for the enhancement of the mechanical performance of Al-Zn-Mg-Mn alloys, while maintaining acceptable electrical properties.

Limitations of Reduction Ratio and Die Angle Optimization for Al-Zn-Mg Alloy Extrusion

While the reduction ratio and the die angle can significantly influence the properties of extruded Al-Zn-Mg alloys, they also present certain limitations. Excessively high reduction ratios can lead to increased extrusion loads, high tool wear, and a potential for surface defects due to excessive deformation. Conversely, very low reduction ratios may result in insufficient plastic deformation, thereby leading to coarse grains and reduced mechanical strength. Similarly, although small die angles promote more uniform metal flow and fine grain structures, they can also increase friction and extrusion pressure, which may reduce the die life. Large die angles, on the other hand, may cause flow instability, non-uniform deformation, and internal defects, such as voids or surface tearing. Therefore, the optimization of these parameters involves a trade-off between mechanical performance, tool longevity, and production efficiency.

Conclusions

Recent studies on the effects of the reduction ratio and the die angle on the properties of extruded Al-Zn-Mg alloys revealed the fact that these extrusion parameters significantly influenced the resulting microstructure and the mechanical properties of the alloys. High reduction ratios generally lead to improved strength and refined grain structures due to increased deformation and dynamic recrystallization. Similarly, the die angle affected the metal flow and strain distribution; smaller die angles promoted a more uniform deformation and finer microstructures but can increase the extrusion force and tool wear. The optimization of both the reduction ratio and the die angle is critical for the balancing of strength, ductility, and process efficiency. Current research also emphasizes the use of numerical simulations and finite element modeling to predict the flow behavior and optimize the die design, to reduce defects and improve product quality in industrial extrusion processes.

Future trends in this study are expected to focus on the integration of advanced simulation tools with real-time process monitoring to optimize the extrusion parameters, more precisely. Machine learning and artificial intelligence are anticipated to play a major role in predicting microstructural evolution and mechanical performance, based on varying reduction ratios and die geometries. Additionally, there is a growing interest in sustainable extrusion practices, such as energy-efficient processing and recycling-friendly alloy formulations. Research will also likely explore the use of hybrid and gradient die designs to tailor properties across the cross-section of the extruded components. These findings may be adapted to additive manufacturing and novel lightweight structural applications, particularly in the aerospace and electric vehicle industries.

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