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Effect of Chemical Composition on Hot Extrudability and Tribological Behavior of 7000 Series Aluminum Alloys

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Abstract. Aluminum 7000 series alloys are widely used for aerospace and transportation applications due to their high strength-to-weight ratio. This research investigates the impact of zinc (Zn) and magnesium (Mg) content on the hot extrudability and tribological behavior. Elemental quantities straight away impact flow stress, determining the manufacturing parameters, whereas galling and adhesion frequently degrade tool life. This work illustrates that by assessing essential ram speeds and temperature limits, adjusting Zn and Mg concentrations considerably improves the extrudability limit. A decreasing flow stress during deformation reduces micro-cracking tendency and improves surface quality. The findings provide critical compositional guidelines for high-strength aluminum alloys, effectively balancing processing efficiency with improved surface quality and reduced element adhesion behavior, ensuring better industrial outcomes for advanced structural components.

Introduction

The 7000 series alloys have an outstanding strength-to-weight ratio, are the strongest commercial class, and are crucial for lightweight aircraft and automotive design [1]. Aluminum is suitable for competitive extrusion, while 7000 series alloys are challenging [2]. Due to a narrow operational window between the highest allowed pressure and the temperature threshold, surface defects limit extrusion speeds [2].

A major defect during hot extrusion of high-strength Al-Zn-Mg-Cu alloys, such as A7075, is surface tearing, which occurs under high-temperature and high-speed conditions [3]. Ngernbamrung et al. demonstrated that the extrudability of AA7075 can be quantified using an Extrusion Limit Diagram (ELD) [4]. Tearing initiates as a solidification crack where heat from die friction, coupled with tension stress at the die exit, causes localized melting of soluble intermetallic compounds like Al_2CuMg and $MgZn_2$ [4, 5]. Ngernbamrung et al. investigated the partial melting that appears as micro-solid bridges rich in Zn, Cu, and Mg on tearing surfaces. These low-melting-point phases, existing at grain boundaries, remain in a semi-molten state during extrusion and cannot withstand the tension forces. Unlike insoluble Al_7Cu_2Fe, soluble precipitates like $MgZn_2$ significantly lower the solidus temperature, thereby serving as primary initiation sites for tearing [4, 5]. Furthermore, concentrated zinc segregation at the vicinity of grain boundaries strongly stimulates tearing sensitivity [6]. The subsequent cooling of this semi-molten region generates tensile stress, which cannot be withstood by the weakened grain boundaries containing large, segregated, insoluble phases like Al_7Cu_2Fe [3]. Therefore, controlling the chemical composition to promote grain refinement and minimize the segregation of these low-melting-point compounds is essential to suppress tearing sensitivity, with grain refinement acting to scatter the concentrated zinc effect [3, 6].

Galling is a critical tribological phenomenon in metal forming causing tool failure via microscopic welding and sharply increased friction [7, 8]. It begins when protective layers (e.g., oxide film, lubricant) are ruptured by high pressure and temperature, exposing reactive material [7]. Alloying elements like Zn and Mg migrate and adhere to the die, drastically worsening surface quality [4, 5].

Prevention involves using high-performance solid lubricants, specialized low-friction die coatings, or modifying tool materials to reduce chemical affinity [4, 7].

Mitigation of tearing relies heavily on controlling friction and temperature at the tool-workpiece interface. Funazuka et al. demonstrated that applying specialized die coatings is highly effective for reducing the friction coefficient, thereby minimizing the process-generated heat that leads to tearing [9]. Furthermore, simulations by Funazuka et al. [10] reveal that process heat generation can significantly elevate the extrudate temperature, potentially exceeding 530°C when using high die temperatures (470°C). Conversely, employing a lower die temperature was shown to suppress this heat buildup, maintaining the extrudate in a safer range of 480–500°C. As higher ram speeds inherently increase process heat, these findings emphasize that effective thermal management is crucial to counteract the temperature rise and mitigate tearing sensitivity, thereby expanding the limited extrudability window of AA7075.

Successful hot forming of 7000 series alloys, particularly through extrusion, hinges on the precise control of chemical composition, especially the Zn to Magnesium Mg ratio [11, 12]. Wang et al. [11] and Jiang et al. [12] note that this fundamental elemental ratio dictates the formation and sequencing of strengthening phases, which in turn governs the microstructure's flow stability at elevated processing temperatures [11, 12]. For instance, lowering the Zn/Mg ratio can effectively suppress recrystallization and promote the formation of discontinuous grain boundary precipitates, a mechanism critical for preventing hot cracking and enhancing the final extrudate quality [12]. Consequently, optimizing this chemical balance is necessary to mitigate flow instability and ensure that the alloy's superior mechanical performance is achievable within a viable manufacturing window [13].

This study systematically prepares and hot extrudes five 7000 series alloys with tailored Zn and Mg contents, analyzing flow stress, mechanical properties, and die adhesion via electron probe microanalyzer (EPMA). The aim of this research is to establish compositional guidelines that expand the extrudability window and successfully mitigate galling phenomena for these high-strength aluminum alloys.

Material and Methods

Five types of billets were conducted using an Al-Zn-Mg-Cu alloy, specifically prepared and cast and homogenized based on the standard A7075 composition. The five resulting specimens labeled A7075, 0Zn, 8Zn, 0Mg, and 4Mg were created by adjusting the Zn and Mg content from 0 to 8 wt.%. The chemical composition of all alloys is presented in Table 1. Billets were cut to 41.5 mm in diameter and 120 mm in length using a turning lathe.

The 200-ton horizontal hydraulic press machine with a container 42 mm in diameter and the extrusion tooling schematic are shown in Fig. 1 and Fig. 2. Container temperature was controlled via heater rods. Ram stroke and extrusion pressure were measured by laser displacement meters and hydraulic pressure transducers. The extrusion tooling assembly used SKD61 tool steel for the die backer, die holder, and dummy blocks. The SKD61 split-type flat die for bearing surface elemental analysis is illustrated in Fig. 3. The split-type flat die was constructed from heat-treated SKD61 tool steel and nitrided. The split-type flat die has a bearing length of 3 mm, a width of 18.6 mm, and a thickness of 1.5 mm. For extrusion, the billets and tooling were preheated at 450–500°C, and the ram speed was 0.5–1.0 mm/s.

Table 1. Chemical composition of the experimental A7000 alloys [wt.%].

	Mg	Si	Fe	Cu	Mn	Cr	Zn	Ti	Al
A7075	2.54	0.09	0.21	1.82	0.05	0.19	5.80	0.01	Bal.
0Zn	2.47	0.09	0.21	1.82	0.05	0.17	<0.01	0.01	Bal.
8Zn	2.48	0.09	0.21	1.87	0.05	0.19	8.13	0.01	Bal.
0Mg	0.01	0.09	0.21	1.83	0.05	0.21	5.50	0.01	Bal.
4Mg	4.89	0.09	0.21	1.84	0.05	0.17	5.78	0.01	Bal.

The extruded profile and sampling procedure are shown schematically in Fig. 4. The extruded section was about 3600 mm long. For surface characterization, three positions relative to the extrusion tip head were chosen. The head at 600 mm, the middle at 1800 mm, and the end at 3000 mm were selected for surface characterization. In the reference coordinate system, the x-axis was the extrusion direction, and the y-axis and z-axis were the profile width and thickness directions. Extrudability was assessed using surface integrity criteria. A successful extrusion had no cracks along the profile length.

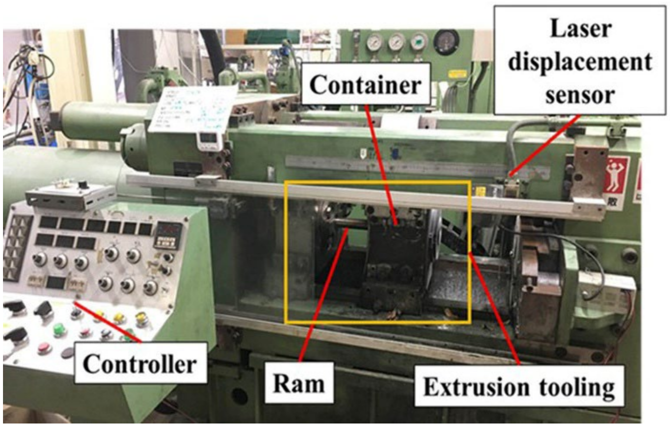


Fig. 1 The 200-ton horizontal hydraulic press machine

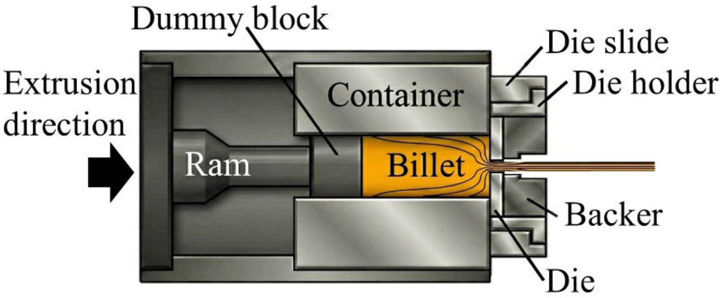


Fig. 2 Schematic diagram of the extrusion tooling

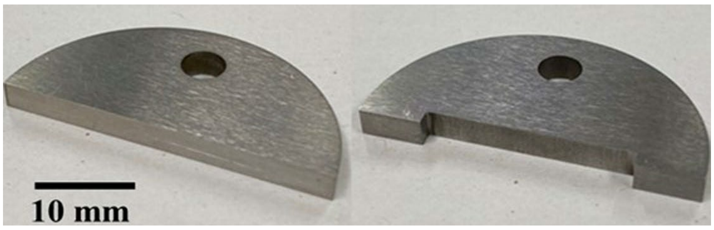


Fig. 3 split-type flat die

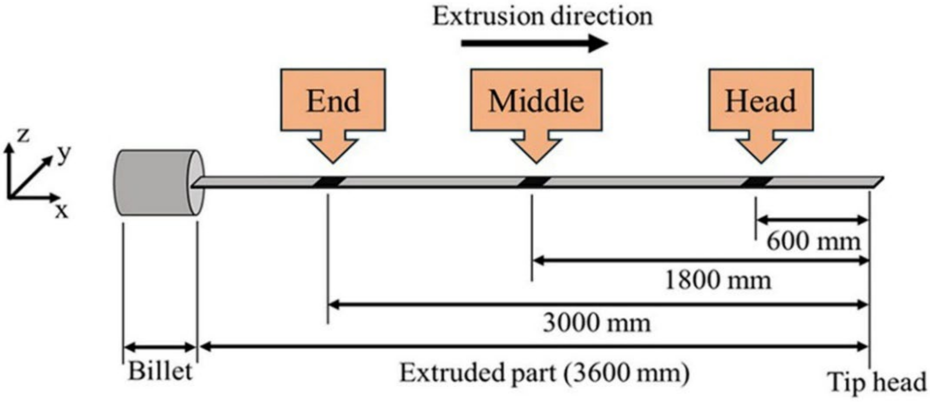


Fig. 4 The position of surface observation

To evaluate the mechanical property changes resulting from high-temperature forming and severe deformation, tensile strength tests were conducted on the material both before and after hot extrusion. Specimens were prepared by cutting the extruded profile into the standard dumbbell shape, as illustrated in Fig. 5, conforming to JIS Z 2241. Tensile specimens were extracted from the center of the extruded profile at the end position (3,600 mm from the tip head), with the longitudinal axis aligned parallel to the extrusion direction. This location was chosen to ensure that no tearing or surface cracks occurred along the entire extrusion length. The tensile tests were performed along this same direction at room temperature using a Shimadzu Autograph AGS-X desktop precision universal testing machine at a constant crosshead speed of 1.0 mm/min. To be sure the results were accurate, at least three tensile tests were done for each experimental condition. The given values for mechanical properties are the average of these tests. The findings indicate very little difference, which means that the experimental data is suitably consistent. Therefore, the curves shown in the figures are representative of these tests.

An electron probe microanalyzer (EPMA JXA-8230) was used to investigate the elements adhered to the split-type flat die bearing surface. The element analysis area on the die bearing surface is shown in Fig. 6. The analyzed elements were selected considering the composition of the 7000 alloy and the oxidation of the die surface. The elemental analysis method was adopted to investigate the adhesion at the bearing surface which is critical for studying friction and tribological behavior thereby predicting the overall tribological performance.

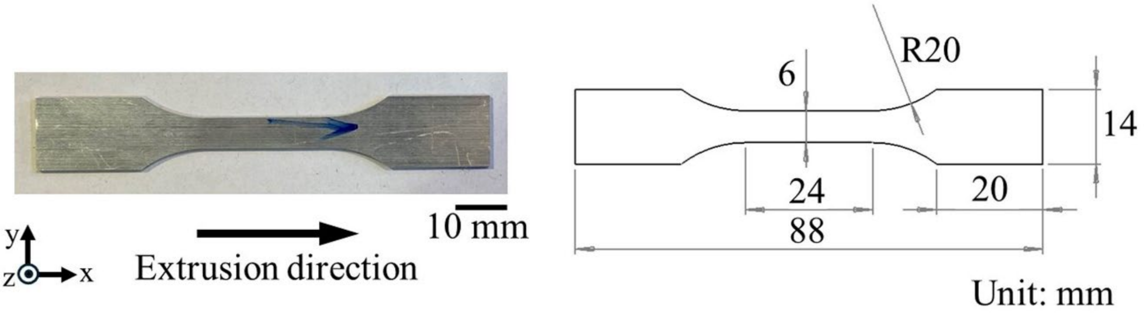


Fig. 5 Tensile test specimen

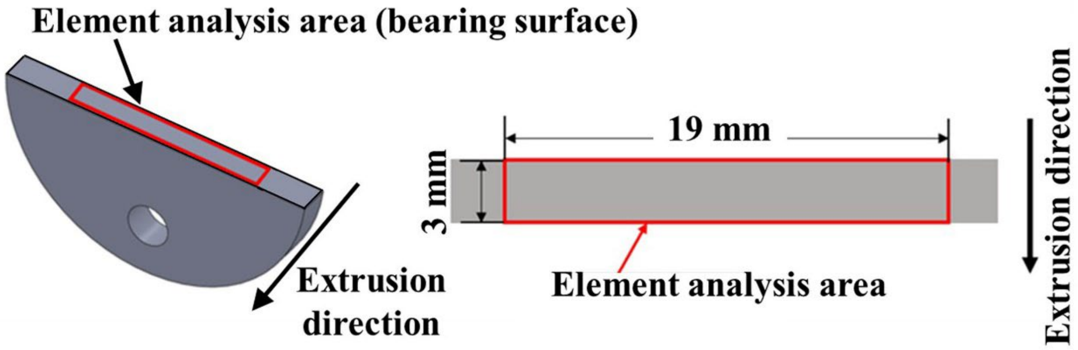


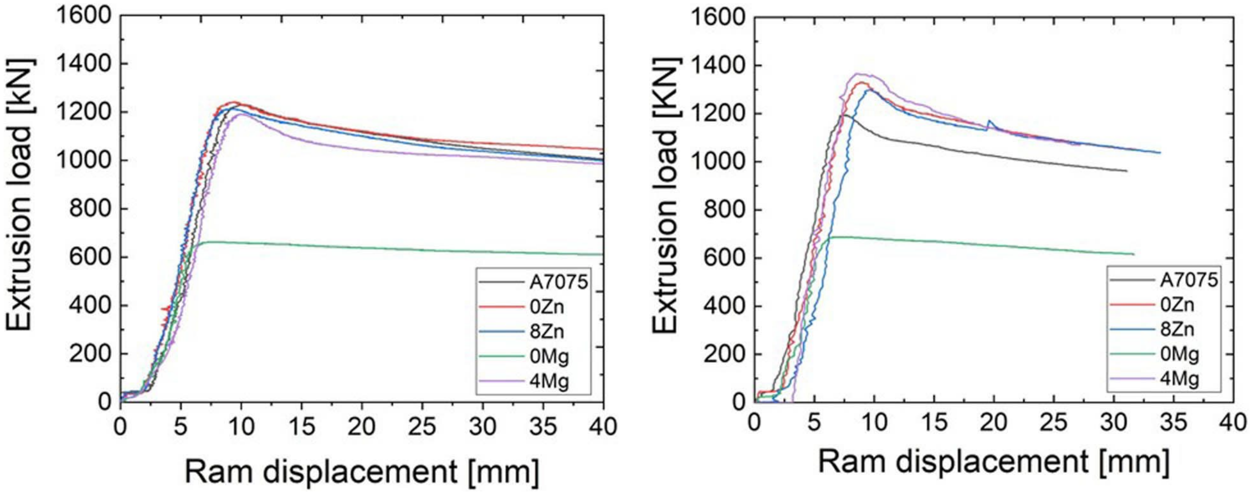
Fig. 6 Element analysis area on die bearing surface

Results and Discussion

The extrusion load behavior was analyzed by comparing load versus ram displacement curves at 500°C under ram speeds of 0.5 mm/s (Fig. 7a) and 1.0 mm/s (Fig. 7b). At 0.5 mm/s, the high strength alloys (A7075, 8Zn, and 4Mg) exhibited peak loads between 1180 and 1220 kN, significantly surpassing the ~660 kN recorded for the 0Mg reference alloy. This disparity persisted at 1.0 mm/s, where peak loads for the high strength group increased further, reaching 1370 kN for the 4Mg alloy, while the 0Mg reference remained substantially lower at approximately 680 kN. Across both conditions, high Zn and Mg content provided strong resistance to deformation. The increase in ram speed led to a universal rise in peak loads, attributed to higher strain rates. The rapid strain rate at

1.0 mm/s limits the time for thermal activation to assist dislocation movement, thereby demanding a higher driving force and elevating flow stress. Additionally, while the post peak load drop was gradual at 0.5 mm/s, it became notably sharper for the high strength alloys at 1.0 mm/s, suggesting reduced stability and increased susceptibility to microcracking and tearing under the heightened thermomechanical load.

The surface appearance of the extruded profiles after hot extrusion at a temperature of 500°C shows a critical dependence on both ram speed and alloy composition, as shown in Fig. 8. At the low speed of 0.5 mm/s, all alloys (A7075, 0Zn, 8Zn, 0Mg, 4Mg) achieve a smooth finish without any surface cracks like tearing. However, when the ram speed is increased to 1.0 mm/s, the alloys with high Zn and Mg content (8Zn and 4Mg) show surface tearing, signifying that their critical extrusion limit has been exceeded. This instability is fundamentally linked to the alloy's initial mechanical properties. The low element composition of 0Zn and 0Mg alloys exhibits a lower hot flow stress, which limits frictional heating and prevents the onset of localized melting of soluble metallic compounds, thus maintaining stability at high speeds. Conversely, the high flow stress of the 8Zn, 4Mg, and A7075 alloys leads to localized overheating near the die bearing, causing the partial melting of low-melting-point soluble intermetallic compounds, specifically Al_2CuMg and $MgZn_2$, along grain boundaries. When the material exits the die, the resulting tension stress acts on this weakened, semi-liquid region, causing the material to fracture via a coagulation cracking mechanism. Furthermore, the presence of insoluble iron-containing phases remaining at the grain boundaries further reduces the intergranular bonding strength, promoting the severe macro-tearing observed on the profile surface.



(a) (b)

Fig. 7 Extrusion load versus ram displacement curves at 500°C with ram speeds of (a) 0.5 mm/s and (b) 1.0 mm/s

Tensile tests performed at ambient temperatures on extruded alloys reveal that Zn and Mg content are critical for strength via precipitation hardening, especially Mg, which has a prominent role as a precipitation particle. The 8Zn alloy had the highest ultimate tensile strength (UTS) at about 500 MPa, while the 0Mg alloy had the lowest strength at about 200 MPa. While all alloys displayed considerable ductility, the higher-strength variants generally showed reduced elongation. The extrusion process, conducted at a high temperature of 500°C and a ram speed of 0.5 mm/s, resulted in a consistent upward trend in UTS and a corresponding decrease in elongation, with A7075 strength rising from 213 MPa to 311 MPa and 8Zn increasing from 387 MPa to nearly 500 MPa. This significant strengthening is attributed to microstructural refinement and the temperature effect induced by the hot extrusion.

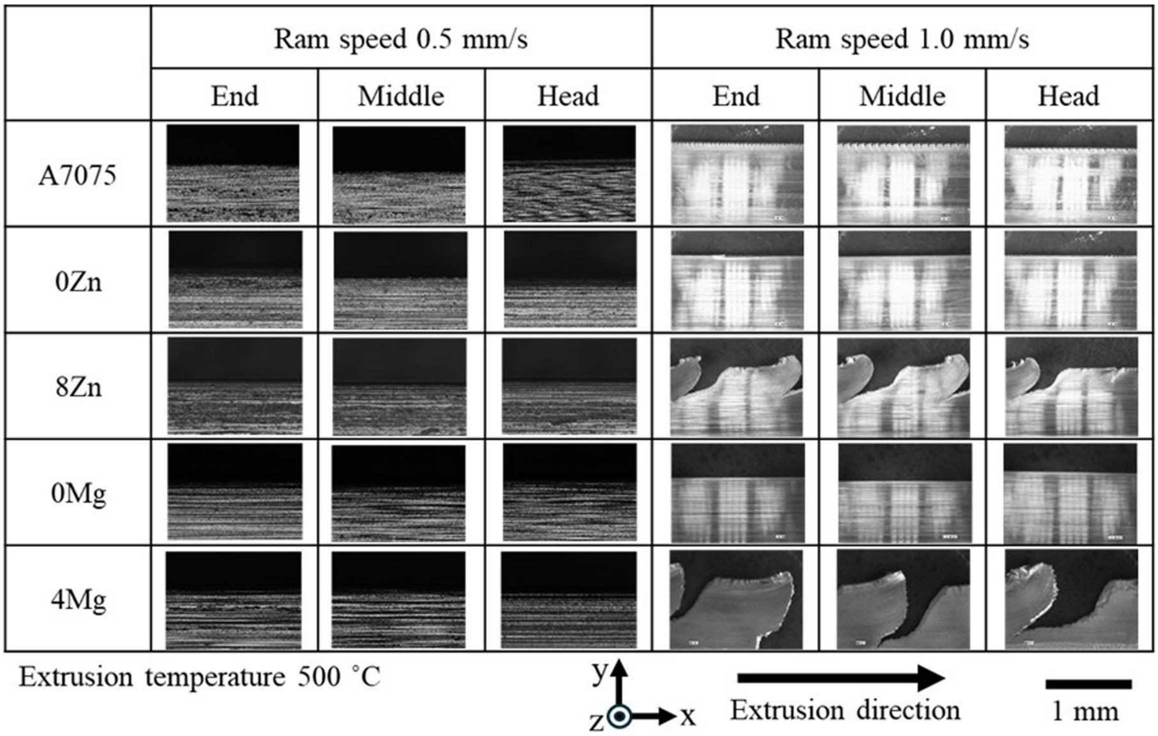
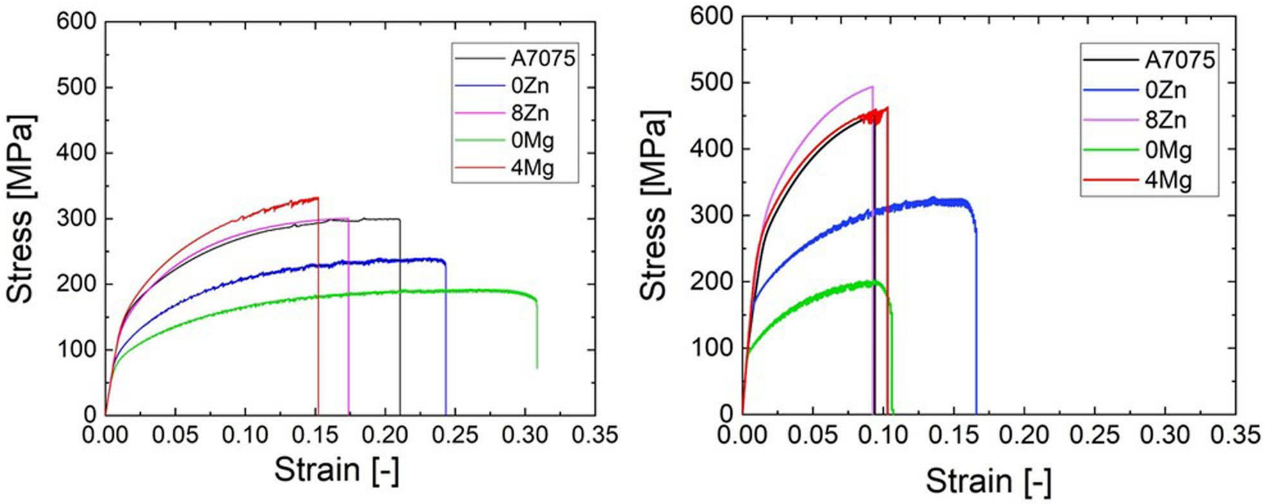


Fig. 8 Surface appearance of extruded profiles after extrusion at 500°C



(a) (b)

Fig. 9 Mechanical properties of alloys (a) before extrusion and (b) after extrusion at temperature 500 °C with ram speed 0.5 mm/s

The results of EPMA elemental mappings for Mg, Cu, Zn, and O, which adhered to the bearing surface of the split-type flat die after a hot extrusion at 500°C with two different ram speeds of 0.5 mm/s and 1.0 mm/s, are presented in Fig. 10 and Fig. 11, respectively, with the color scale indicating relative concentration from low to high. At the ram speed of 0.5 mm/s, it was found that alloys with a high Mg content showed Mg, Cu, Zn, and O adhering more closely at the die entrance than at the exit. At the same time, alloys with a high Zn content showed Zn, Cu, and O adhering throughout the surface, except for the examination of Mg, which still exhibited clear adhesion behavior at the entrance. In addition, it can be observed that in alloys containing both Mg and Zn, the adhesion of the two elements significantly overlaps at the entrance of the die bearing surface.

At a ram speed of 1.0 mm/s, element adhesion is observed, comprising Zn and Mg, usually accompanied by surface oxidation. The research reveals a strong relationship between billet composition and adhesion intensity, with A7075 and 8Zn alloys showing the most severe galling due to the higher chemical bonding and reduced melting points of Zn and Mg. In contrast, 0Zn and 0Mg alloys exhibited markedly decreased elemental transfer, despite the presence of an Al-rich base layer. The adhesion phenomenon is caused by the localized melting of low-melting-point intermetallic compounds, such as Al_2CuMg and $MgZn_2$, at the tool's surface interface as a result of significant frictional heating. These semi-molten phases accelerate the transfer of material to the die, enhancing friction and causing surface tearing. Therefore, accurately controlling the Zn and Mg concentrations is essential for reducing galling and increasing the extrudability of all high-strength aluminum alloys.

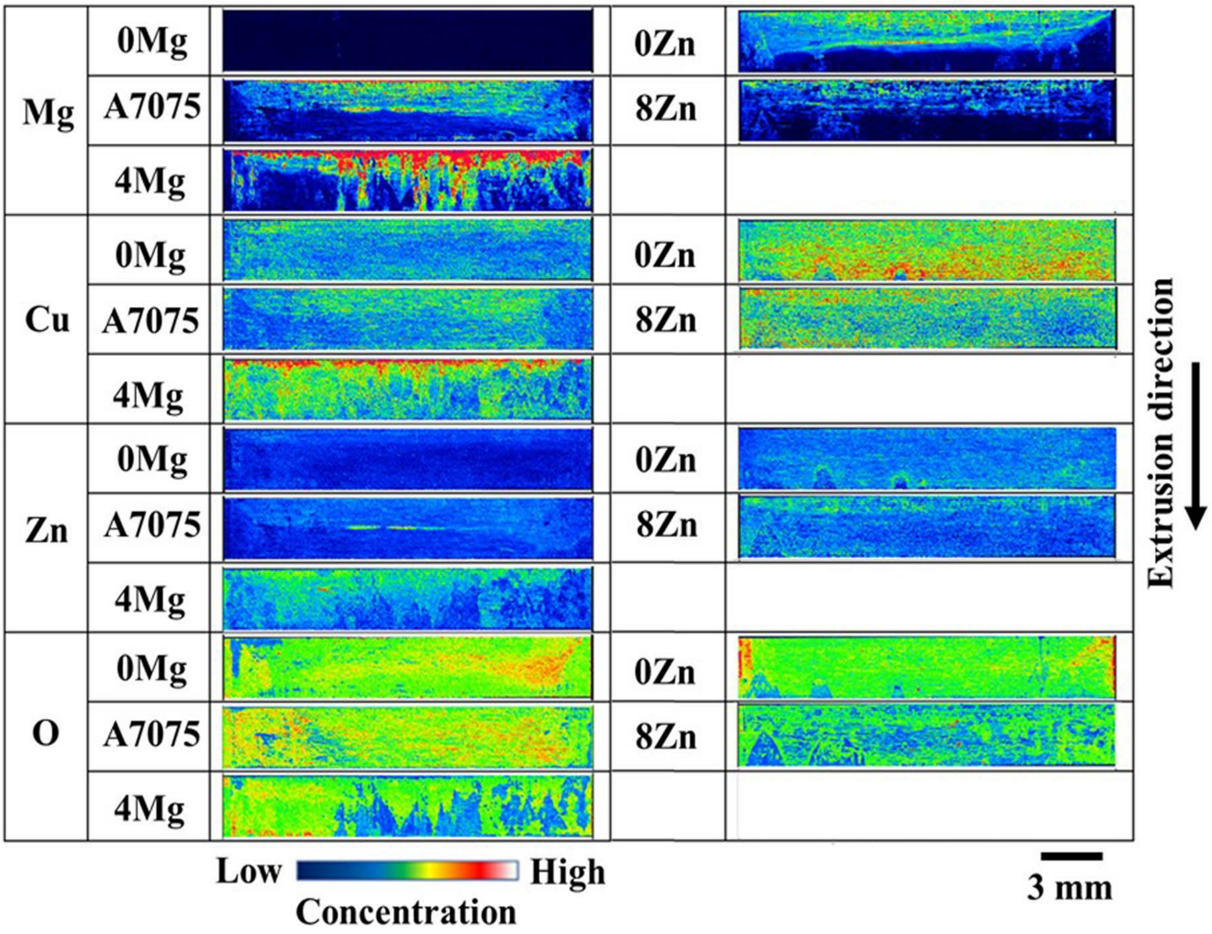


Fig. 10 The analysis of element maps by EPMA (Temperature 500 °C and ram speed 0.5 mm/s)

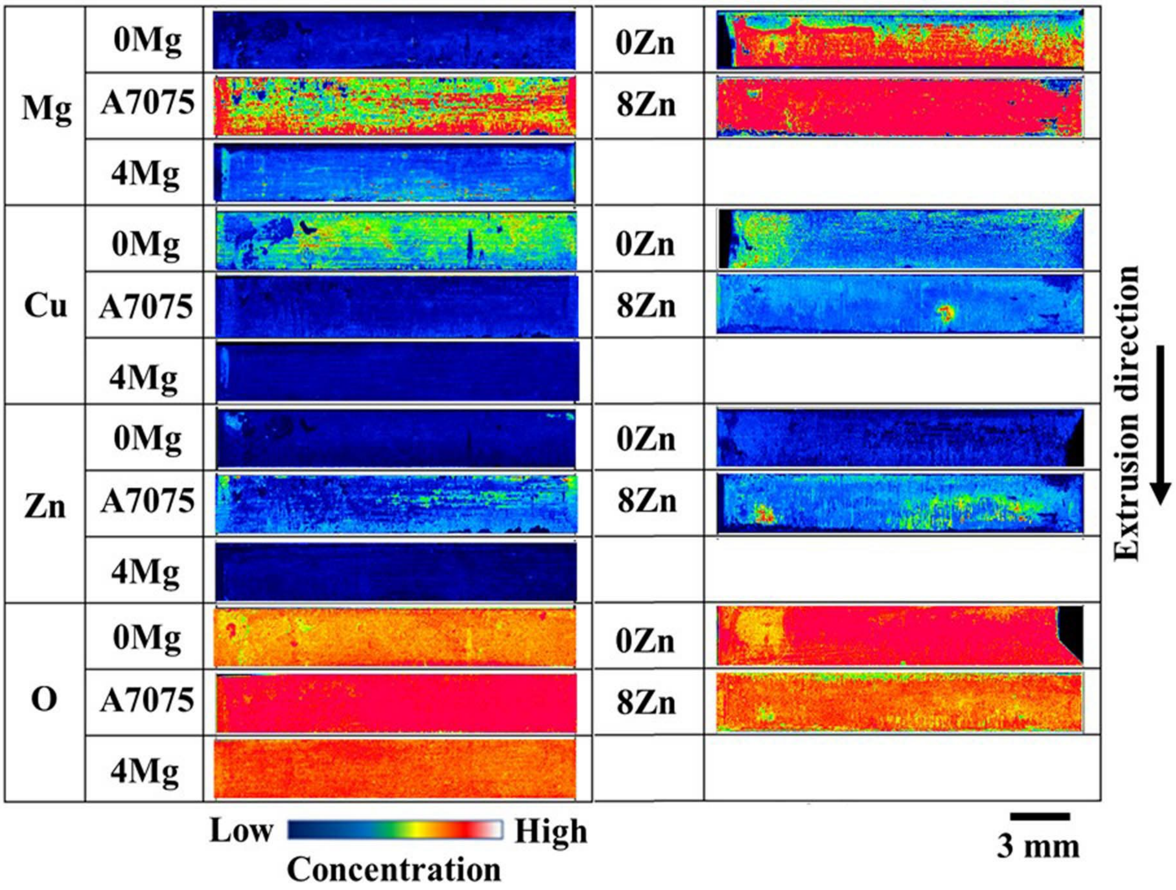


Fig. 11 The analysis of element maps by EPMA (Temperature 500 °C and ram speed 1.0 mm/s)

Conclusions

This study demonstrates that the chemical composition, specifically the concentrations of Zn and Mg, significantly affects the hot extrudability, mechanical properties, and tribological performance of 7000 series aluminum alloys. To achieve improved mechanical properties through precipitation hardening, significant amounts of Zn and Mg are required. Thus, the 8Zn variation has an ultimate tensile strength of about 500 MPa. However, these elements also raise hot flow stress and limit the optimum processing window. At increased ram speeds, localized frictional heating induces the melting of soluble intermetallic compounds at grain boundaries, thereby weakening intergrain bonding and resulting in surface tearing through a process of cracking mechanism.

Moreover, tribological investigation via EPMA revealed that the adhesion of alloying elements and die galling is sensitively proportional to both composition and speed, with increased ram speeds markedly increasing material transfer and surface oxidation. High magnesium content induces concentrated adhesion at the die entry, while elevated zinc content causes more extensive adhesion across the bearing surface, both of which accelerate surface tearing under high-speed conditions. Therefore, adjusting the Zn/Mg ratio is essential for achieving a balance between high mechanical strength and manufacturing feasibility, as it enhances the extrudability window by decreasing intermetallic segregation and mitigating adverse tool-workpiece interactions for 7000 series aluminum alloys.

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