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CONTRASTING MAGNESIUM AND ZINC ADDITIONS IN AA6061 ALUMINUM ALLOY: MICROSTRUCTURAL AND MECHANICAL PERFORMANCE VIA FRICTION STIR PROCESSING

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ABSTRACT

The present study examines the comparative effects of magnesium (Mg) and zinc (Zn) additions on the microstructural and mechanical behavior of the AA6061-T6 aluminum alloy modified by friction stir processing (FSP). The elements were added in various amounts (1–5 wt.%), and their effects on grain refinement, precipitation behavior, tensile strength, hardness, and ductility were investigated. Adding magnesium produced a more refined structure, with the most potent effect at 3 wt.%, yielding the best ultimate tensile strength of roughly 194 MPa and the best hardness. For Zn, at 5 wt.% peak strength reached values around 230 MPa, representing an increase of 48% compared to the base alloy, with microhardness exceeding 130 HV. Zn is better than Mg for maximizing strength and hardness. But if you want a strength-ductility balance, which is what you need in something that must have toughness, then you want Mg. This analysis indicates that compositional optimization of AA6061 can change its properties and behavior via FSP.

Keywords: Metal matrix composite, Mg/Zn particle reinforcement, Friction stir processing, Microstructural, Microhardness

1 INTRODUCTION

One of the most widely used alloys in aerospace among the heat-treatable 6xxx series is AA6061 aluminum alloy. Although it has an excellent balance of properties, increasing requirements for the weight reduction and performance make it necessary to improve its strength and ductility. [1], [2]

The use of alloying additions can be regarded as one of the most important methods of improving the properties of aluminum alloys. [3] Zinc (Zn) and Magnesium (Mg) deserve particular attention due to their different modes of action. [4] While Zn is the main alloying element in 7xxx series and acts as an alloying addition to 6xxx series providing solid solution strengthening and improving the formation of $MgZn_2$, it also increases the hardness and tensile strength and gives some corrosion resistance. [5], [6] On the contrary, Mg being the key element in 6xxx and 5xxx series alloys mainly

contributes to solid solution strengthening and precipitation hardening, improving the ductility and corrosion resistance. [7], [8]

Friction Stir Processing (FSP), which is a variation of Friction Stir Welding (FSW), is a powerful solid-state technique used to modify the microstructure and surface. [9] Numerous studies have confirmed that FSP can significantly increase the properties of aluminum alloys. Uday et al. reported grain refinement and increased hardness of FSP-treated AA6061. [10] Kalashnikova et al. showed an increase in tensile strength and ductility of the particle-reinforced FSP composites. [11] Kumar et al. also revealed that metallic/ceramic reinforcement could significantly enhance the hardness and wear resistance of 6xxx alloys. [12]

Recent research shows the possibility of using the method of FSP for in-situ alloying where the pre-deposited elements, e.g., Zn or Mg, are introduced into the matrix forming a new microstructure. However, the comparison between the effects of Zn and Mg addition in FSP-processed AA6061 is currently missing, which makes it difficult to understand their different strengthening mechanisms. Therefore, this paper aims to fill this gap by analyzing the influence of Zn and Mg pre-deposition on the microstructure, hardness, and tensile properties of AA6061-T6 alloy treated by FSP.

2 MATERIALS AND METHODS

2.1 Materials Selection

In the present experiment, the base metal (**BM**) utilized is 6061-T6 aluminum alloy. plates measure 150 mm in length, 100 mm in width, and 2 mm in thickness. The chemical composition and mechanical properties of the base material are listed in **Tables 1 and 2**, respectively. **Mg** and **Zn** powder particles are introduced into a hole created at the interface of AA6061-T6 plates. The average particle sizes of the **Mg** and **Zn** powders are 31.8 μm and 83 μm , respectively.

Table 1: Chemical Composition of AA6061-T6

Element	Al	Si	Mg	Cu	Cr	Fe	Zn/Ti/Other
Wt. %	Balance	0.4–0.8	0.8–1.2	0.15–0.4	0.04–0.35	≤ 0.7	Trace

Table 2: Mechanical Properties of AA6061-T6

UTS (MPa)	YS (MPa)	Elongation (%)	Hardness (HV)
290	255	10	105

2.2 Tool Design and Preparation

The tool design featured a cylindrical, straight pin with a height of 1.8 mm and a diameter equal to one-third of the shoulder diameter (18 mm), as shown in **Figure 1**.

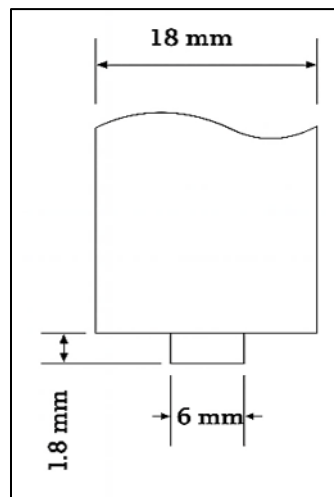


Figure 1: Schematic diagram of the FSP tool

2.3 Friction Stir Processing Procedure

The mixing phase involved horizontal movement of the milling table at a feed rate of 24 mm/min with a constant tool rotation of 900 rpm and a tilt angle of 2.5°.

Different mixing ratios were implemented by drilling holes of various diameters along the processing line as shown schematic in **Figure 2**. **Table 3** shows the mixing volume percentage and the corresponding hole dimensions. Initial trials with a zigzag double row pattern failed due to defect formation, and therefore only single rows were used.

$$\begin{aligned}\text{volume of welded zone} &= \text{Dia. Of shoulder} * \text{width of welded} * \text{thickness of welded} \\ &= 16 * 50 * 2 = 1600\end{aligned}$$

$$\text{volume of holes} = \text{volume of cylinder} * \text{No. of holes}$$

Table 3: Mixing ratios and corresponding hole dimensions

Sample	Dia.	volume of holes	volume of welded zone	≅ vol. %
1	0	0	1600	0
2	1.5	19.0755	1600	1%
3	2	33.912	1600	2%
4	2.5	52.9875	1600	3%
5	3	76.302	1600	5%

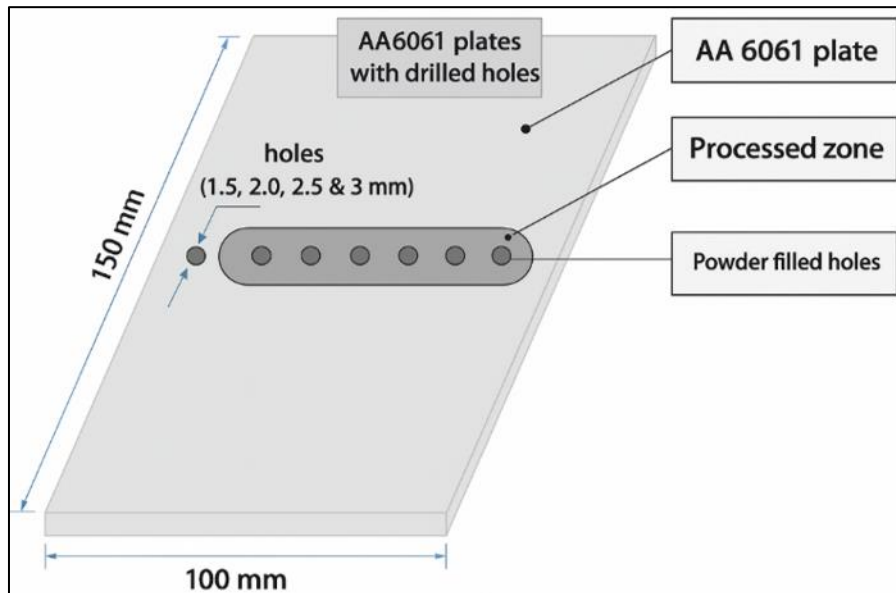


Figure 2: Mixing zone schematic

2.4 Mechanical Testing

Tensile testing was carried conformed to ASTM B557M standards also Vickers microhardness testing (HV0.5) was performed on **FSP**-processed specimens (Seven indentations were taken along the top surface of each sample)

3 RESULTS AND DISCUSSION

3.1 Introduction

This section presents and discusses the results of the microstructural and mechanical characterization of AA6061-T6 aluminum alloy reinforced with varying percentages of **Mg** and **Zn** through **FSP**.

3.2 Microstructural Observations

From the microstructural analysis for the investigated Al-Mg alloys with 1-5 wt.% Mg presented in Figure 3, is apparent an increasing development of the morphology, distribution, and density of β - Al_3Mg_2 intermetallic phase within the α -Al matrix, directly affecting the mechanical properties of these alloys. The addition of magnesium contributes to the formation of the β - Al_3Mg_2 phase by means of eutectic reactions between aluminum and magnesium, preferentially occurring along the grain boundaries and, in larger amounts, even inside the grains.

Due to an increase in the content of magnesium, there will be a higher number of particles of the β - Al_3Mg_2 intermetallic phase, uniformly distributed, resulting in better precipitation hardening by blocking the dislocation glide mechanism. The refining process of the morphology of this phase (from coarse and separated particles to finer and elongated ones), results in maximum precipitation hardening. From the results obtained from the current study, it can be seen that the alloys having a larger amount of magnesium have better hardness and tensile strength values, similar to those of previous works on Al-Mg alloys.[13], [14] where it was mentioned that fine and evenly distributed β -phase particles enhance the yield strength due to Orowan strengthening mechanism.

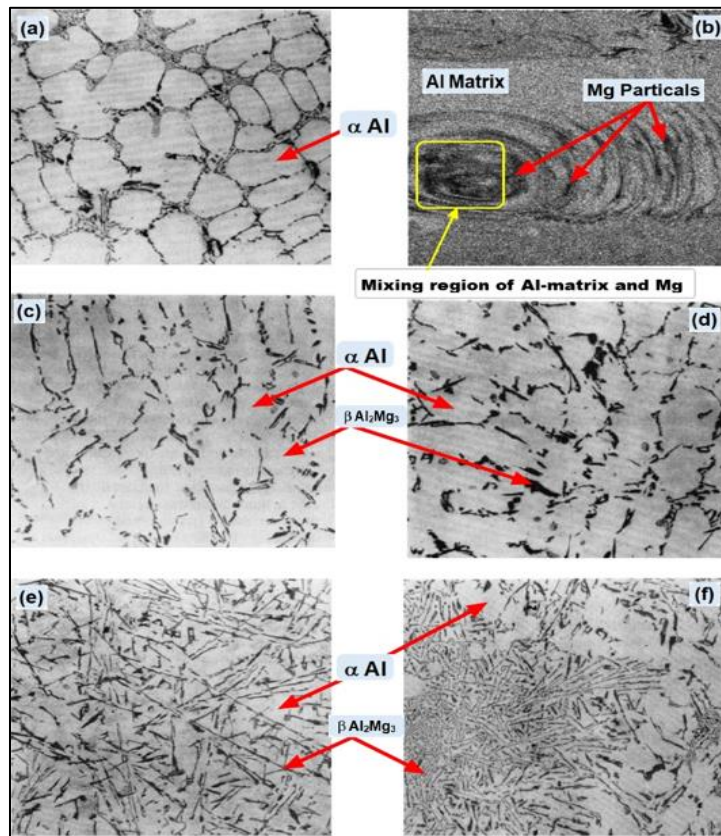


Figure 3: Optical microscope image of the (a) pure aluminium (b) Mg-reinforced Al-matrix composite (c) 1 Wt. % Mg (d) 2 Wt. % Mg (e) 3 Wt. % Mg (f) 5 Wt. % Mg

Intermediate content of magnesium in the alloy provides a very good balance between tensile strength, hardness, and moderate ductility due to the stable and fine morphology of the β - Al_3Mg_2 phase. However, higher content of magnesium causes coarsening of the intermetallic phases in the same way as in other high-magnesium aluminum alloys, causing a decrease in the effectiveness of the dislocation pinning and thus reducing strength and hardness. The SEM micrographs and EDS analysis prove the presence and morphology of the β - Al_3Mg_2 intermetallic phase within the aluminum matrix. Fracture surface micrographs, Figure 4, (a, c, and d) show a clear lamellar eutectic structure, resulting from the reaction between aluminum and magnesium during solidification with the β - Al_3Mg_2 intermetallic phase distributed along grain boundaries and inside the matrix.

The EDS spectrum Figure 4. (b) shows the elements composing this phase, including aluminum, magnesium and also silicon, which may be related to the formation of ternary intermetallic phases in localized regions.

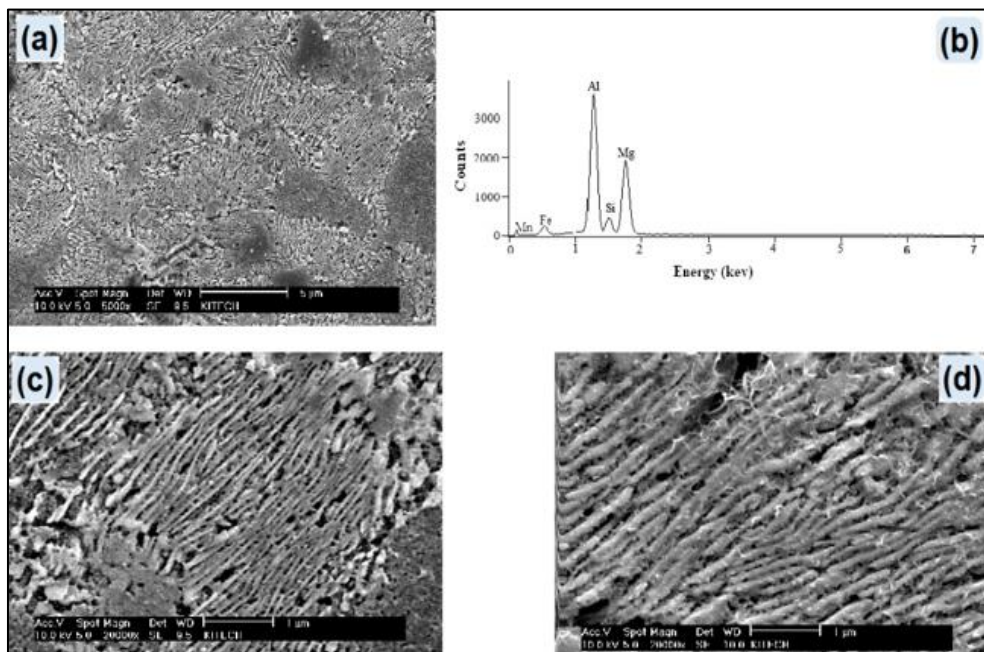


Figure 4: (a, c, and d) SEM image of the 3 Wt. % Mg-reinforced Al-matrix composite (b) the EDS at 3 Wt. %

Microstructural characteristics of the Al-Zn alloy systems having 1-5 wt. % of Zn, as seen from Fig. 5 (a-f), demonstrate the tendency to gradual change in precipitate morphological features, dispersion degree and density in the α -Al matrix, which is well related with the mechanical properties of the alloy. Addition of Zn leads to the formation of small-size Mg-Si-Zn rich β'' and Q' precipitates in the matrix and the possibility of appearance of η ($MgZn_2$) precipitates along grain boundaries due to the Zn content increase.

With increasing of Zn concentration to the intermediate one (2-3 wt.%), micrographs show the growth in the number density of precipitates with their more even distribution in the matrix. This can be associated with the expected acceleration of precipitation kinetics in Zn-containing Al-Mg-Si-Cu systems. The fine and dense network of β'' (Mg-Si-Zn) and Q' precipitates provide an efficient precipitation hardening effect leading to high hardness and strength values with relatively fine grain size. Such strengthening effects were found by [15], [16] who discovered the significant improvement in mechanical properties of 6xxx series alloys with moderate Zn additions due to the combined precipitation and grain refinement mechanism.

With high content of Zn (5wt.%) the microstructure is characterized by the highest precipitate density and finest size with the presence of both intragranular Mg-Si-Zn phases and separate η -phase precipitates along grain boundaries.

SEM images in Fig. 6. (a, c, and d) show fine precipitates in the matrix. These precipitates are formed from Zn of the alloy composition. EDS spectrum in Fig. 6. (b) confirms the presence of Al as a matrix phase and prominent peaks for Zn, Mg, and Si proving the successful addition of zinc and its possible segregation into Mg-Si precipitates or the formation of η ($MgZn_2$) phase at grain boundaries.

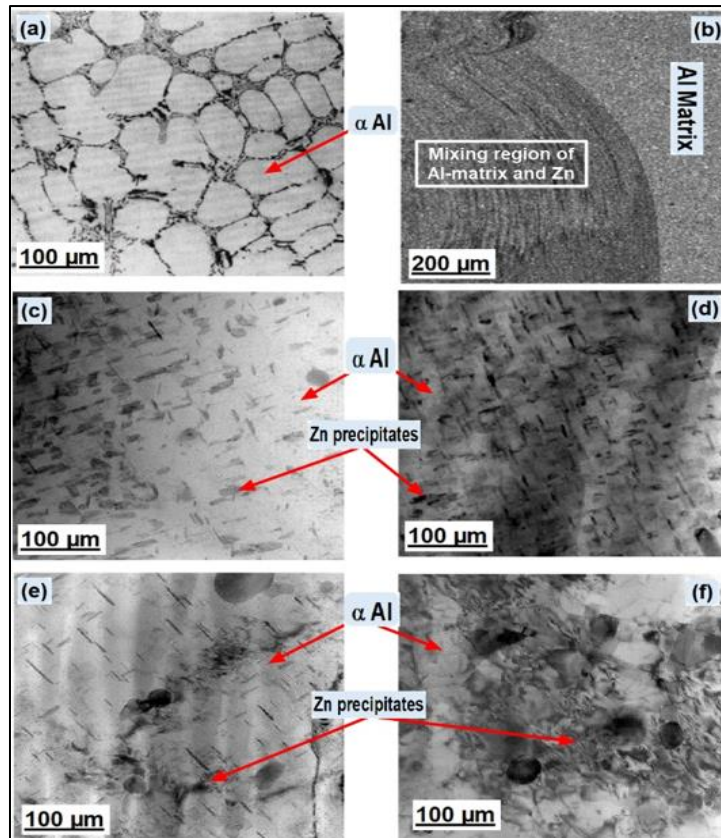


Figure 5: Optical microscope image of the (a) pure aluminium (b) Zn-reinforced Al-matrix composite (c) 1 Wt. % Zn (d) 2 Wt. % Zn (e) 3 Wt. % Zn (f) 5 Wt. % Zn

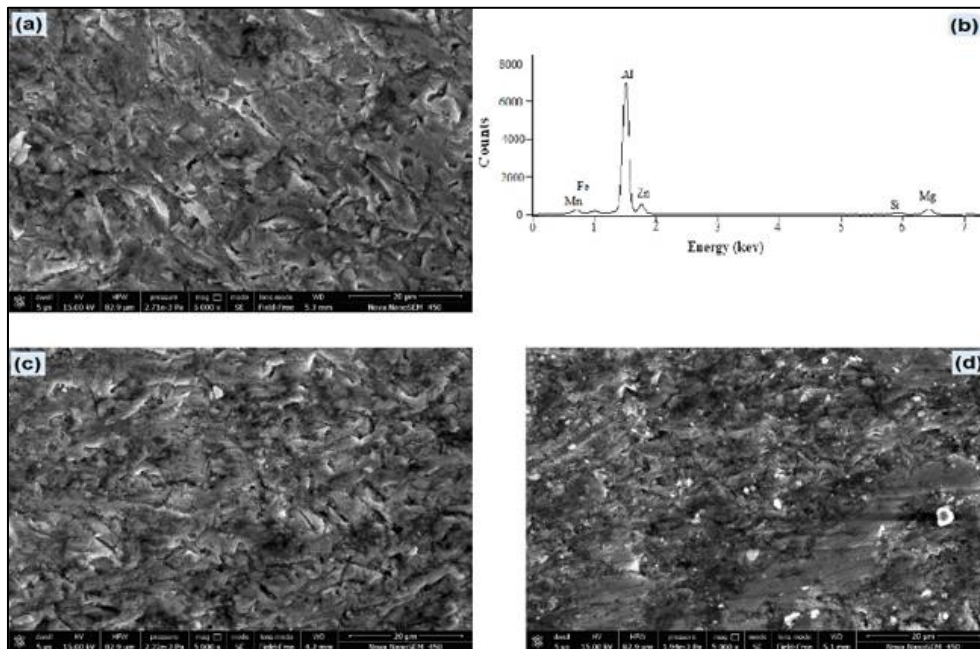


Figure 6: (a, c, and d) SEM image of the 3 Wt. % Zn-reinforced Al-matrix composite (b) the EDS at 3 Wt. %

3.3 Tensile Properties

Figure 7. illustrates the effect of different magnesium concentration (0-5 wt. %) on the ultimate tensile strength (UTS), mechanical efficiency, ultimate elongation (UEL) and total elongation (TEL) of AA6061-T6 aluminum alloy subjected to friction stir processing (FSP).

Base alloy had UTS of 155MPa, UEL of 31 and TEL of 52. With increasing weight percentage of Mg, UTS slightly decreased and both UEL and TEL. When weight percent of Mg increased to 2wt%, the improvement in strength and efficiency became pronounced reaching 108%. However, ductility further decreased because of possible formation of brittle phases. Optimum mechanical properties were obtained for 3 wt. % Mg addition where AA6061-T6 alloy had maximum UTS of 194MPa and efficiency of 125%. This could be attributed to grain refinement and solid solution strengthening. Although elongation values were further reduced (UEL: 20%, TEL: 28%), the strength-ductility ratio at this stage was favorable.

With increasing the magnesium concentration to 5 wt. %, UTS and efficiency became slightly reduced. Even though the values were still higher than those of base alloy, this reduction together with further decrease in ductility (UEL: 21%, TEL: 30%) indicated the presence of brittle intermetallic phases such as Mg_2Si which compromised mechanical integrity.

These trends were in accordance with literature data. It is known that addition 3wt% Mg promoted the formation of coarse β - Mg_2Si particles. Proved that high magnesium concentrations adversely affected the grain boundary cohesion leading to early failure of the specimens under tensile stresses.[13]

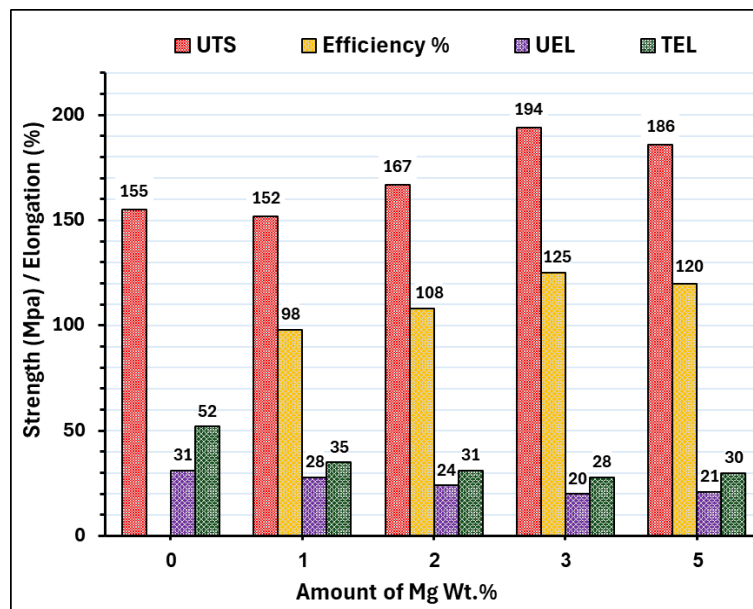


Figure 7: Maximum UTS, YS, UEL, and TEL bar graph of Mg Wt.% reinforced Al-matrix composite

Figure 8. illustrates the effect of different zinc concentration (0-5 wt.%) on the ultimate tensile strength (UTS), yield strength (YS), ultimate elongation (UEL) and total elongation (TEL) of AA6061-T6 aluminum alloy subjected to Friction Stir Processing (FSP).

The addition 1 wt. % of Zn caused the increase in UTS and mechanical efficiency, which was attributed to the enhancement in strength response. Further enhancement in tensile strength was observed with increasing Zn content to 2wt.%. At 3 wt.% Zn, UTS increased to 205 MPa and efficiency reached maximum of 132%. The highest strength response was observed at 5 wt.% Zn where UTS reached 230 MPa and represented a significant increase of about 48% compared to unreinforced base alloy, 148% Efficiency. The positive effect of Zn addition on tensile properties was confirmed. However, ductility values dropped considerably (UEL: 20%, TEL: 22%), what could be associated with the formation of brittle intermetallic phases or Zn segregation, resulting in the premature fracture.

The results were in agreement with literature data. It is known that high content of Zn in aluminum alloys leads to the formation of coarse secondary phase particles such as $MgZn_2$ or Al-Zn intermetallic which acts as stress concentrators.[17] It was also noticed that zinc additions above 3 wt.% could negatively affect ductility regardless of its beneficial influence on strength because of grain boundary embrittlement.

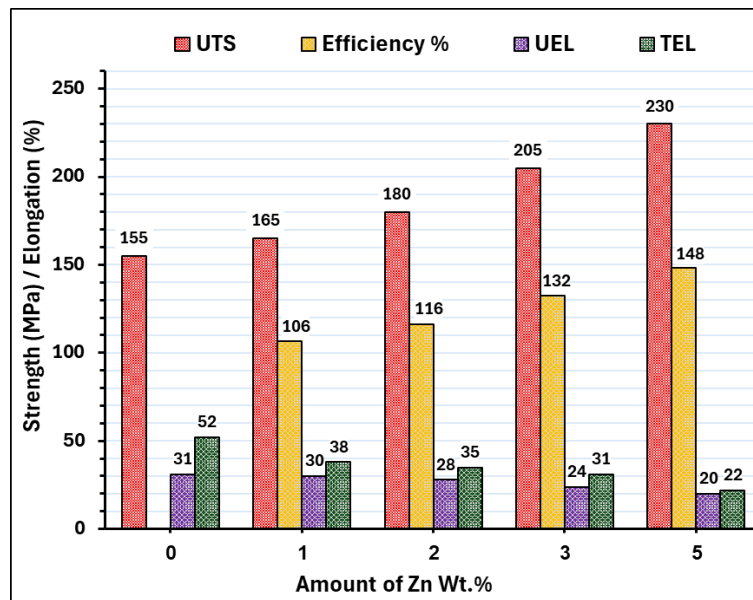


Figure 8: Maximum UTS, YS, UEL, and TEL bar graph of Zn Wt.% reinforced Al-matrix composite

3.4 Comparative Discussion: Influence of Mg and Zn on Mechanical Response of AA6061-T6 Processed via FSP

Comparative analysis of Mg and Zn additions into AA6061-T6 alloy by means of FSP is shown in Figure 9 and shows distinctive strengthening behavior and deformation characteristics, mainly due to metallurgy of interaction of each element with aluminum matrix. It is known that Mg additions showed less pronounced effect on tensile strength of alloy, but maintained comparatively high ductility especially at elevated concentrations. Zn additions caused more prominent increase in tensile strength and mechanical efficiency compared to Mg.

Different strengthening characteristics of Mg and Zn could also be explained from the thermodynamic and diffusivity standpoint. The Zn with lower melting point and fast diffusion rate in aluminum compared to Mg could lead to the growth or agglomeration of precipitates under severe thermal cycles of FSP, particularly multi-pass FSP. Mg which had low diffusivity provided the formation of fine thermally stable precipitates including semi-coherent phases during cooling.

In conclusion, Zn offered high-strength property, which made it preferable for the applications with high strength-to-weight performance. On the contrary, Mg showed the good balance between strength and ductility, which made it preferable for the applications with tough deformation properties.

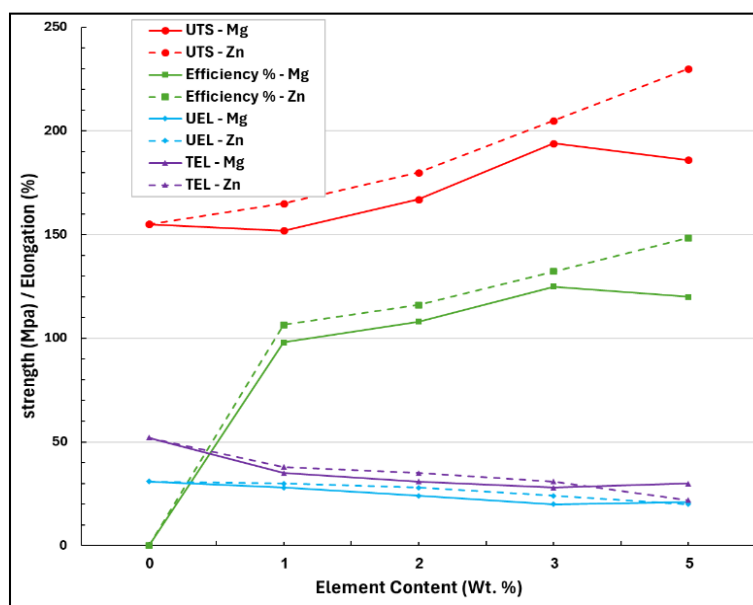


Figure 9: Comparison of Mg and Zn Wt.% on mechanical properties of AA6061-T6 via FSP

3.5 Microhardness Distribution

Figure 10. Vickers microhardness plot of AA6061-T4 alloy having different percentage of Mg particle reinforcements (1, 2, 3, and 5 Wt. %). It can be seen that the maximum hardness value has been achieved in stir zone. Particularly 1% and 2% of Mg reinforced composites gave maximum hardness value of 65 HV and 62 HV, respectively. While the minimum hardness was reported in the heat-affected zone HAZ, with values not exceeding 45 HV. The lowest hardness value of about 41 HV is obtained by 5 Wt. % Mg sample.

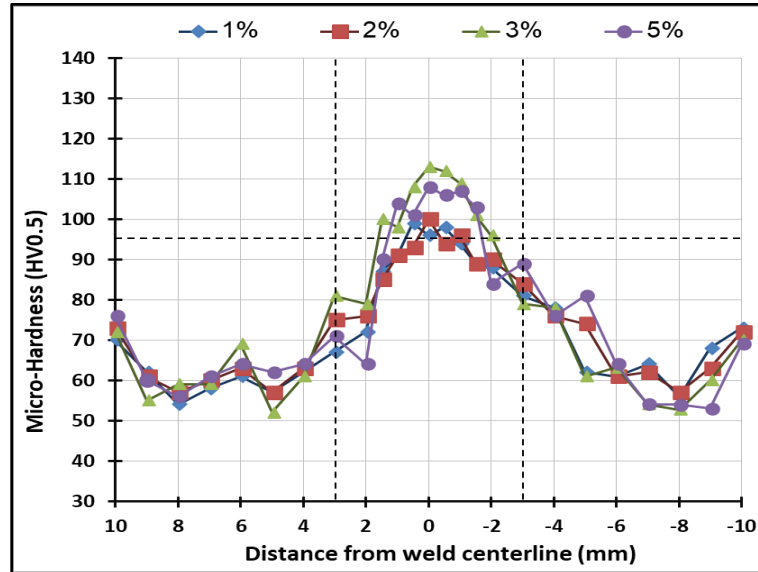


Figure 10: Microhardness variation curve of Mg particle reinforced Al-matrix composite

On the other hand, Figure 11 shows the variation curve of microhardness of the Zn-reinforced AA6061-T6 alloy produced by friction stir processing. The graph shows a remarkable increment in hardness along the weld zone, especially in its centerline. With the increasing zinc content from 1 wt.% to 5 wt.%, there is a steady increment in the hardness of the peak values near the stir zone (SZ) to about 134 HV at 5 wt.% Zn. It is to be noted that the hardness of base metal and heat-affected zones (HAZ) remain nearly the same with typical hardness of about 65-75 HV, corresponding to the T6 temper of the AA6061 alloy.

The thermal characteristics of Zn particle are of great significance in this regard. Zinc with a melting point of about 420 °C—much lower than that of Al-Zn particles starts melting and diffusing much earlier in the aluminum matrix in FSP operation. The high diffusivity accelerates the kinetics of phase formation, helping in refining the grains through dynamic recrystallization.

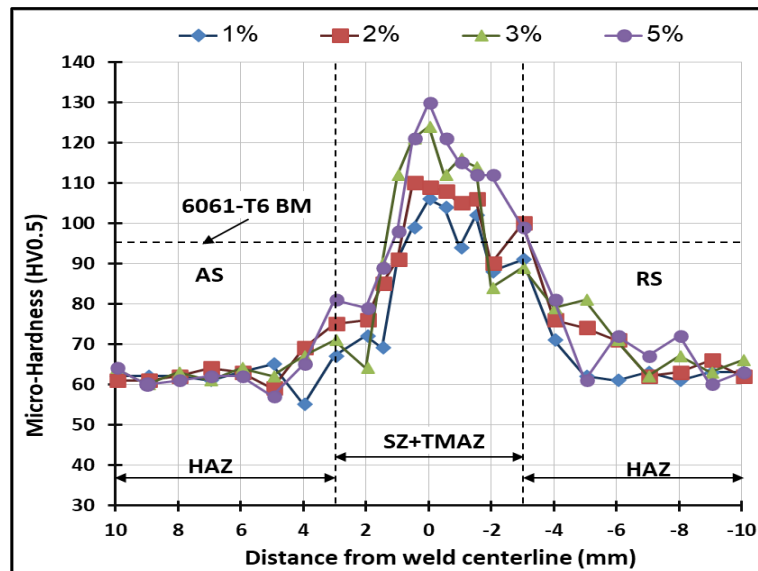


Figure 11: Microhardness variation curve of Zn particle reinforced Al-matrix composite

3.6 Comparative Discussion of Peak Microhardness Behavior

The bar chart comparing peak microhardness at the weld centerline (0 mm) of different addition levels of Mg and Zn into AA6061-T6 alloy using FSP process as shown in Figure 12. It is evident that the microhardness values of Zn additions are considerably higher than magnesium for all levels, showing that Zn addition exhibits better hardening effect through various reasons.

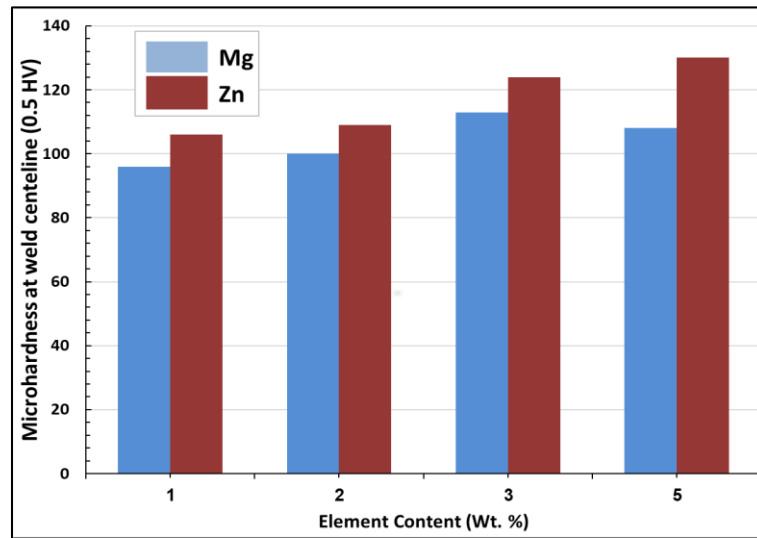


Figure 12: Peak Microhardness vs. element content for Mg and Zn additions

First, the metallurgical reasons for improved microhardness can be due to the precipitation of fine intermetallic compounds like $MgZn_2$ and Al-Zn rich precipitates. While, Mg tends to form coarse Mg_2Si particles which do not give much strengthening effect. Secondly, thermally speaking, since Zn has lower melting point ($\sim 420^\circ\text{C}$) as compared to Mg ($\sim 650^\circ\text{C}$) it leads to early softening and higher diffusion kinetics in FSP leading to improved atomic mobility.

4 CONCLUSION

This research paper undertakes an in-depth analysis of the influence of Mg and Zn addition on the microstructural and mechanical characteristics of AA6061-T6 aluminum alloy subjected to FSP. From the obtained results, it is clear that both elements considerably increase the alloy strength through different metallurgical processes, but their effects on ductility, hardness, and microstructural stability are not identical.

The most optimal results in terms of the highest values of UTS, microhardness, and satisfactory ductility are achieved when using 3 wt.% Mg. The Zn addition demonstrates a higher strengthening effect, leading to an increase in UTS by up to 48% and reaching microhardness values of over 130 HV with 5 wt.% Zn.

On the whole, Zn is more effective in the case of strength and hardness maximization and can be used as the material with high wear resistance, while Mg is preferable because of the better combination of strength and ductility. However, future studies are needed to develop post-FSP heat treatment procedures aimed at overcoming the problem of the ductility decrease after high alloying.

STATEMENTS ON COMPLIANCE WITH ETHICAL STANDARDS

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