Investigation on the effect of titanium (Ti) addition to the Mg-AZ31 alloy in the as cast and after extrusion conditions on its metallurgical and mechanical characteristics

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Abstract. Magnesium-aluminum alloys are versatile materials which are used in manufacturing a number of engineering and industrial parts in the automobile and aircraft industries due to their strength – to –weight -ratios. Against these preferable characteristics, magnesium is difficult to deform at room temperature; therefore it is alloyed with other elements mainly aluminum and zinc to add some required properties particularly to achieve high strength -to- weight ratio. Grain refinement is an important technology to improve the mechanical properties and the microstructure uniformity of the alloys. Most of the published work on grain refinement was directed toward grain refining aluminum and zinc alloys; however, the effect of the addition of rare earth material on the grain size or the mechanical behavior of Mg alloys is rare. In this paper the effect of Ti addition on the grain size, mechanical behavior, ductility, extrusion force and energy, of Mg-AZ31 alloy both in the as cast condition and after direct extrusion is investigated.

1. Introduction
The increasing demand for light weight structures has forced the industry to look for new effective methods to produce light weight alloys. A major problem which hampers the wide spread such alloys like aluminum and magnesium alloys is their limited formability when the conventional manufacturing techniques are used. Magnesium and its alloys are the lightest constructional available materials on earth with a maximum density of 1.78 gm/cc and melting point of 650 °C, with good damping characteristics, but difficult to deform at room temperature, [1]. Magnesium and its alloys have a maximum density of 1.78 gm/cc. Mg and its alloys oxidize rapidly, accompanied by exothermic reaction, which may catch fire; therefore care must be taken during their machining. However products of Mg and its alloys are not fire hazard. Mg and its alloys are used in a wide variety of structural and nonstructural applications. Structural applications include automotive applications such as clutch and pedal support brackets and steering column lock housings. They are also used in industrial machinery such as textile and printing machines. Furthermore, they are used in commercial applications which include hand held tools, computer housings and ladders. Mg alloys are very useful in the parts which operate at high speed to minimize the inertial effect due to their light weights. They are also valuable for aircrafts due to their high strength- to- weight- ratio and good stiffness both at room and elevated temperatures. The ductility of magnesium alloys in the cold state is low; therefore it is recommended that these alloys are worked at hot temperatures. They are typically combined with
manganese, aluminum, zinc, or zirconium for different applications and they can be used to produce components with superior mechanical properties. Magnesium and its alloys have recently received a great attention over the last decade, due to the increasing demand for the light weight structural materials replacing other metals in several industrial and engineering applications, [2]. Grain refinement is an important technology for improving the mechanical properties; surface quality and workability of both cast and wrought alloys. Grain refinement has an industrial history stretching back to 1949 when Cibula showed that the presence of Ti, particularly in combination of carbon or boron, produced a great refining effect in Al. Since then it became an industrial practice to grain refine Al and its alloys by adding Ti or Ti+B to the melt prior to solidification. Al-Ti binary and Al – Ti –B ternary master alloys are developed and commercially available for this purpose, [3-4]. Later, the grain refinement of zinc alloys was investigated in an attempt to enhance their potential to be used in many industrial applications, especially in the automotive and aircraft industries, [5]. Due to the great demand of Mg and its alloys, they have received great attention from the researchers to drive out results of their benefits focusing on achieving methods that might lead to refine the grains of the Mg alloys. Research works were conducted to test the formability of the Mg-AZ31 alloy and how it can be improved; it was found that as the Al content of the alloy increases, yield strength, ultimate tensile strength and the oxidation resistance all will increase; whereas the cast ability of the alloy will decrease, [6]. Later, a new equal channel angular extrusion (ECAE) processing was applied to control the microstructure and mechanical properties of AZ31 Mg alloy resulting in a very fine grains and a significant increase in both the ductility and yield stress of the alloy after the processing. Further results showed that the grain refinement in AZ31 magnesium alloy was successfully carried out using the ECAP (Equal Channel Angular Pressing) processing at different temperatures; reducing the grain size nearly four times after 2 passes of ECAP under 250 °C with a homogeneous grains. This also resulted in increasing the hardness, [7]. Research works were conducted to test the formability of the Mg-AZ31 alloy and how it can be improved; it was found that as the Al content of the alloy increases, yield strength, ultimate tensile strength and the oxidation resistance all will increase; whereas the castability of the alloy will decrease. The effect of Al on the alloy ductility, or maximum elongation during tensile testing, is less predictable since Al is capable of either increasing or decreasing mechanical strength depending upon the used heat-treatment. Initially, Mg-AZ31 alloy was also refined by adding alloying elements like Al-Ti-C master alloy with different Ti concentrations resulted in an efficient grain refinement of the alloy microstructure; this was explained by the forming of Al4C3 and TiC particles; it was also noted that the higher the percentage of Ti in the master alloy, the more efficient the grain refinement process, [8-9]. Researchers have also examined the superplastic behavior of the Mg-AZ31 alloy after extrusion and processing by the ECAP; it was demonstrated that an elongation of around 460% may be attained at a temperature of 150 °C, which reflects the potential for achieving superplastic behavior at low temperatures. Room temperature tensile properties of a superplastic Mg-AZ31 alloy were examined showing that the alloy behaved in a superplastic manner at low strain rates. The formability of the Mg-az31 alloy sheets at warm working conditions was investigated, [10,11]. The effect of subjecting the Mg-AZ31 alloy to severe plastic deformation after the addition of a grain refiner is rare. This formed the main objective of this work. In this paper, the effect of the addition of Ti to Mg-AZ31 alloy on its metallurgical and mechanical aspects in the cast and after direct extrusion is investigated.

2. Materials, equipment and experimental procedures

2.1 Materials

The following materials and alloys were used in this work:

Mg- AZ31 alloy, very high purity Ti and aluminum of 99.98 % purity and a flux made of 47% potassium chloride, 5% barium chloride and 48%Mg chloride to avoid oxidizing of the melt inside the electrical furnace. The Mg-AZ31 alloy was imported from China and the very high purity Ti and aluminum were supplied by ARAL, Arabic Co for manufacturing aluminum products.
2.2 Equipment and experimental procedure
The experimental procedure started with the design and manufacturing of the forward extrusion die followed by the preparation of the Mg-AZ31 and its microalloys before and after extrusion for the following tests: Vickers micro hardness test, standard tensile tests for mechanical behavior determination and specimens for metallurgical examination: grain size and photomicrographs of the general microstructure for each microalloy. All specimens were machined on a CNC machine under the same cutting conditions of speed, depth of cut and feed rate.

3. Results and discussion
3.1 Effect of Ti addition on the grain size of Mg-AZ31 in the cast and after extrusion
The histogram shown in Figure 1 indicates that the addition of Ti to Mg-AZ31 alloy resulted in refining its grain size in the as cast condition; the grain size was reduced from 22 to 19 μm. Similarly, the histogram of Figure 1 also shows that the extrusion process resulted in further refinement of the grains of the Mg-AZ31 grain refined by Ti. The decrease in the grain size being 27% and 26% respectively. This agrees with previous findings in the literature. This is attributed to the heavy plastic deformation caused by the extrusion process. The grain refining effect is explicitly illustrated in the photomicrographs of Figure 2 (a), (b), in the as cast condition and Figure 3 (a), (b), after extrusion for Mg-AZ31, and Mg-AZ31-Ti respectively.

![Histogram showing grain size comparison before and after Ti addition](image1.png)

**Figure 1.** Effect of Ti addition on the grain size of Mg-AZ31 in the as cast and after extrusion

![Photomicrographs](image2.png)

**(a) Mg-AZ31 (22 μm)**

**(b) Mg-AZ31-Ti (19 μm)**

**Figure 2.** Photomicrographs of Mg-AZ31 and Mg-AZ31-Ti in the as cast condition
3.2 Effect of Ti addition on the mechanical characteristics and formability of Mg-AZ31 both in the cast and after extrusion conditions

Figures 4 and 5 show the mechanical behavior of Mg-AZ31 and its microalloys both in the as cast condition and after extrusion respectively as determined from the compression tests. These figures indicate enhancement in its mechanical strength by Ti addition particularly at larger values of strain. This is in general agreement with the results reported by in [12-14].
Table 1 gives a summary of the mechanical characteristics of Mg-AZ31 alloy and its microalloy Mg-AZ31-Ti in the as cast condition.

| Mg-AZ31 and its microalloys | Flow stress (MPa) at strain=20% | General equation of mechanical behavior | Strength coefficient (k) MPa | Strain hardening index (n) |
|-----------------------------|---------------------------------|----------------------------------------|-----------------------------|---------------------------|
| Pure Mg-AZ31                | 230.1                           | $\sigma = 292 \varepsilon^{0.148}$    | 292                         | 0.148                     |
| Mg – AZ31 –Ti               | 241.3                           | $\sigma = 398 \varepsilon^{0.311}$    | 398.1                       | 0.311                     |

It can be seen from Table 2 that the addition of Ti to Mg-AZ31 caused an increase in both the strength coefficient of the Mg-AZ31 alloy and the flow stress at 20% strain; this is attributed to the hard particles of the intermetallic compounds of aluminides as discussed previously. Regarding the work hardening index, it can be seen that it has also increased by the addition of both Ti; this indicates better formability i.e. it can be formed to a larger strain before plastic instability occurs which in return will reduce the number of stages in the forming process when preforms are involved because the representative strain equals the strain hardening index ($\varepsilon = n$) at plastic instability. Table 2 shows the mechanical characteristics of Mg-AZ31 and its microalloys after the extrusion process. It clearly indicates that the extrusion process resulted in increase of the work hardening index from 0.148 to 0.299 for the Mg-AZ31 and from 0.311 to 0.366 for the Mg-AZ31-Ti.

| Mg-AZ31 and its microalloys | Flow stress (MPa) at strain=20% | General equation of mechanical behavior | Strength coefficient (k) MPa | Strain hardening index (n) |
|-----------------------------|---------------------------------|----------------------------------------|-----------------------------|---------------------------|
| Pure Mg-AZ31                | 38.9                            | $\sigma = 63 \varepsilon^{0.299}$     | 63                          | 0.299                     |
| Mg – AZ31 –Ti               | 39.2                            | $\sigma = 70.7 \varepsilon^{0.366}$   | 70.7                        | 0.366                     |

3.3 Effect of Ti Addition on the Hardness of Mg-AZ31 both in the Cast and After Extrusion Condition

The effect of Ti addition on the hardness of Mg-AZ31 alloy both in the cast and after extrusion conditions is shown in the histogram of Figure 6. The histogram indicates that the addition of Ti to Mg-AZ31 alloy resulted in increase of its Vickers microhardness both in the as cast condition and after extrusion. This enhancement in case of Ti addition may be attributed to the formation of hard particles of the intermetallic compounds within the main matrix.

![Figure 6. Effect of Ti addition on the hardness of Mg-AZ31 both in the as cast and after extrusion conditions](image-url)
3.4 Effect of Ti addition to Mg-AZ31 on the extrusion force and energy

The experimental values of extrusion force and energy for the Mg-AZ31 alloy and its microalloy are determined from the autographic records of the extrusion process. Figures 7 and 8 shows the autographic records of the extrusion process of pure Mg-AZ31 and Mg-AZ31-Ti respectively. These curves were used to determine the extrusion force and energy as summarized in Table (3). It can be seen from this table that the extrusion force was reduced by 57% while energy of Mg-AZ31 was reduced by 59% with the addition of Ti.

The Effect of extrusion conditions on microstructure and mechanical properties of micro alloyed Mg–Sn–Al–Zn alloys is given in [12] and the effects of Extrusion Speed on the Microstructure and MechanicalProperties of Mg-9Gd—3Y—1.5Zn—0.8Zr alloy is forwarded in [13].

| Alloy           | Extrusion Force (N) | Extrusion Energy (J) |
|-----------------|---------------------|----------------------|
| Pure Mg-AZ31    | 15,365              | 207                  |
| Mg – AZ31 – T   | 6,598               | 85.3                 |

3.5 Effect of Ti Addition to Mg-AZ31 on the ductility

The determination of ductility for the Mg-AZ31 and Mg-AZ31- Ti was obtained successfully in the as cast condition by the maximum elongation % and the maximum reduction in cross sectional area % as shown in the histograms of Figures 7 and 8 respectively, whereas after extrusion, it was not possible to obtain enough length of the extruded specimens of the Mg-AZ31 alloy and Mg-AZ31-Ti microalloy, although several tests were conducted, and the specimens from them were fractured after extruding 12 mm as shown in the photographs of Figures 9a and 9b for Mg-AZ31 and Mg-AZ31-Ti respectively. Typical extrusion autographic records of the Mg-AZ31 and its Mg-AZ31-Ti microalloy are shown in Figures 10a and 10b respectively. The significant effect of adding trace amounts of Ti on the high temperature deformation behavior of fine-grained Mg–6Al–1Zn magnesium alloy is reported in [14].

Figure 7. Effect of Ti addition on the maximum elongation % of Mg-AZ31 in the cast condition

Figure 8. Effect of Ti addition on the maximum elongation % of Mg-AZ31 in the cast condition
4. Conclusions
The following points are concluded:
In the cast condition:
Addition of Ti to Mg-AZ31 alloy at 0.15 wt. % resulted in grain refining of its structure and increase of its mechanical strength e.g. its flow stress, strength coefficient and hardness. Furthermore, it resulted in improvement of its ductility and work hardening index \( n \), hence improving its formability. Although the addition of Ti to the Mg-AZ31 resulted in increase of its flow stress, it caused decrease in both the extrusion force and energy compared to the Mg-AZ31 alloy.
After extrusion the extrusion process has resulted in further refinement of both Mg-AZ31 alloy and Mg-AZ31-Ti alloy. It also resulted in further enhancement of their flow stress, work hardening index, formability, ductility and hardness. Finally it is concluded that the Mg-AZ31 cannot be extruded at room temperature. Furthermore despite the previously gained advantages by the addition of Ti to the Mg-AZ31 it was not possible to be extruded at room temperature.

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