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# Mechanical Properties and Machinability of Magnesium Alloy AZ31 and AZ91 – A Comparative Review

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**Abstract.** Throughout the last decade magnesium alloys have slowly overtaken aluminium alloys, especially in the automotive and aerospace industry. Due to its attractive weight-resistance and weight-hardness characteristics, the global production of Magnesium alloys has grown from 360,000 tons in 1999 to 850,000 tons in 2013. Magnesium alloys AZ91 and AZ31 are the most widely used grades. AZ 91 exhibits a Knoop's hardness (HK) of 76.2 that is higher to the AZ31 with a 51.1 HK. The manufacturing of AZ 91 is through a casting process whereas AZ31 is manufactured by using an extrusion process. The microstructure of AZ31 and AZ91 are highly influenced by the heat generated during the machining process that also affects the surface hardness due to the high thermal conductivity of the material that range from 62 W/m.k to 96W/m.k. Both materials have a very good machinability where milling, drilling, and turning are commonly used. However, extreme care should be taken in terms of machining conditions as Magnesium alloy is highly flammable. However, a safe machining process can be performed by avoiding very fine chips, magnesium dust and also the usage of water-based coolants that react with the raw material. This paper has widely reviewed the studies that have been conducted since the evolution of magnesium alloys in terms of machining parameters, machining consumables and their effect on the mechanical properties, surface conditions and limitations of the various machining processes.

Keywords: Magnesium alloy AZ31, magnesium alloy AZ91, microstructure hardness

## 1. Introduction

Magnesium is in the group 2 in the periodic table and its symbol is Mg. The density of pure magnesium is 1.745 g/cm<sup>3</sup> which are currently the lightest metal on the market [1]. At room temperature, pure magnesium is weak and lack strength that is needed to be considered as a structural base material. This condition is enhanced with the addition of alloys like Aluminium (Al), Zinc (Zn) and other elements. Shi et al. stated that the addition of aluminium brings more strength and hardness to the final alloy [2]. It also contributes to the smooth casting process as it stretches the overall freezing range of the alloy. Gziut et al. observed in their study that an excess of 6 wt% of Al has shown a positive effect on the quality of heat treatment of the alloy even though a lower value also offers a good combination of strength and ductility [3]. On the other hand, the same authors noticed that the addition of Zinc improves both the strength at room temperature and corrosion resistance against impurities such as iron and nickel. In addition, Manganese element have a minor role in the composition of Mg alloy as it will only create an intermetallic with some potential corrosive impurity elements such as iron and other heavy earth material to reduce their corroding ability in the alloy [3]. In a further study, Atwell et al. concluded that the addition of Manganese in the alloy chemical composition is merely when its application is met for a



very corrosive environment such as being in contact with sea water [4]. Next, Yang et al. highlighted in their experimental works that the hardenability of the mechanical properties of Mg alloy is enhance with the inclusion of silver. Silicon element is widely use in most alloy composition and its main purpose in Mg alloy is to increase the overall fluidity of the molten metal as well as the creep resistance of the alloy with the formation of  $Mg_2Si$  particles that will stick to the grain boundaries. The presence of the rare earth element in Mg alloy is to decrease the appearance of porosity and crack in castings by reducing the freezing range of the alloy. Magnesium alloy is use in many industries such as in aviation, medical, electronics and automobile. The main reason that it has been use in the transportation industry is to produce a lighter body structure that is a very critical factor to increase fuel economy and at the same time reduce pollution. The density of magnesium is 33% lighter than aluminium and four times lighter than steel. Apart from being light, Magnesium alloy have an excellent specific strength and stiffness, exceptional dimensional stability, high damping capacity, and high recycle ability [5]. Akyuz found out that Mg alloys can be classified as AM (Al, Mn), AZ (Al, Zn), and AS (Al, Si) series Mg alloys. Nevertheless, in terms of machining of Mg alloys, the author observed that by using the most convenient type of cutting tools and combination of process parameters, the risk of ignition can be reduced. On the other hand, applying a higher cutting speeds in the turning process have shown a high possibility of chip ignition but lowering the cutting forces may contribute to reducing this risk [6]. The same author also mentioned that the production process for Mg is mostly by casting and extrusion process. Next, the author also stated that machining of parts that are made of Mg alloy is quite common especially for those dedicated to the aviation and automotive industry. A very high cutting speed can be applied but serious concern has arisen that there is a high risk of flank build up (FBU) due to adhesion between the cutting tool and the workpiece together with the high risk of ignition.

## 2. Mechanical Properties

The mechanical properties of Mg alloys AZ31 and AZ91 are quite different to each other due to their chemical composition. Table 1 shows some of the main mechanical properties between Mg alloys AZ31 and AZ91. In a study by Sunil et al, that was investigating on the characteristics of both Mg alloys, they found out that AZ91 shows higher brittleness and hardness due to the high level of aluminium that created a compound known as  $Mg_{12}Al_{12}$ . The Vickers hardness for the AZ91 was in the range of 80-120 Hz and that of AZ31 was only in the range of 70-95 Hz. According to this experiment, it was suggested that the formation of  $Mg_{12}Al_{12}$  was the main cause of the high hardness. It was also observed that the length of the indent was  $33\mu m$  when applied to a region dominated by the  $\beta$ -phase compared to other regions containing  $\alpha$ -phase and  $\alpha+\beta$  phase that were only in the range of  $36-48\mu m$ . This data confirm that  $\beta$ -phase is harder than other phases [7].

**Table 1.** Elements for AZ31 and AZ91 alloys

Material	Elements (wt%)							Mg
	Al	Zn	Mn	Si	Cu	Ni	Fe	
AZ31	3.05	0.82	0.40	0.020	0.003	0.0012	0.0023	Bal.
AZ91	8.80	0.71	0.19	0.029	0.002	<0.001	0.0010	Bal.

Table 1 shows the chemical composition for Mg alloy AZ31 and AZ91. The major difference between these two grades is the highest wt. % of aluminium content in the AZ91 which enhance the hardness of the alloy when it is combined with the other elements.

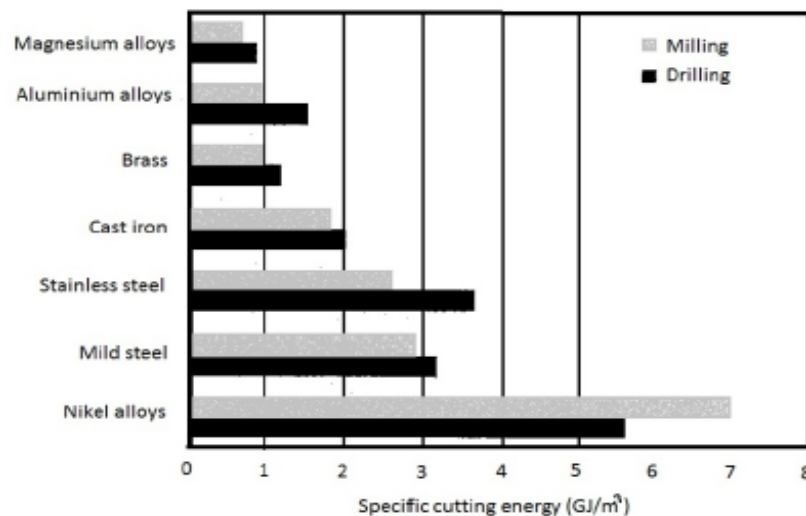
Aluminium (Al) is one of the most important elements in magnesium alloy. Al is among the few material that can easily dissolve in magnesium. In addition, the solubility limit of aluminium at eutectic temperature is 11.5 at wt.% (12 mass %) and falls to about 1% at room temperature [9]. The aluminium content in both AZ31 and AZ91 contribute largely to providing a better mechanical property, corrosion resistance, and dies-castability. However, it was observed that at a temperature of above  $125^{\circ}C$ , the creep resistance tends to be lower that limit the application of this alloy for some components [9].

Currently, Mg12Al12 is not suitable for some automotive parts such as automatic transmission cases due to its high operating temperature that can go up to 175°C whereas an engine block operating temperature can go up to 200°C and an engine piston, even higher than [10-12]. According to Yang et al., the creep resistance is another essential mechanical property to be taken into consideration specially when dealing with selected automotive parts that generate high temperature during their operation. Further development is underway to create a more effective heat resistant magnesium alloy. They can be divided into three categories which are the alloying of Mg-Al based alloys with Calcium (Ca), the combination of Mg based alloys with Zirconium (Zr) and Rhenium (Re) and the addition of zinc (Zn) to magnesium. Moreover, it was reported in a US patent whose authors were Bronfin et al., that the addition of Ca to Mg-Al was met to improve the creep resistance and it was tested in another works conducted by Hollrigl-rosta et al. which concluded that an improvement was observed when 1% of Ca was added to AZ81 [13,14]. In a further study, it was reported that a calcium level of about 1% in Mg alloy can create casting defects such as cold-shuts, hot cracking, and die-sticking. On the other hand, when the Ca levels increases to 2 % the problems were less significantly or completely reduced [15]. The authors also observed that the addition of strontium (Sr) was very efficient in enhancing the corrosion resistance when combine with Mg alloy.

The increase of the aluminium content to 5% and the addition of 1.2 to 1.8% of strontium were demonstrated by Pekguleryuz and Barai that it increases the tensile properties of magnesium alloy as well as the creep resistance of the overall magnesium alloy compare to conventional alloy [16]. Further research on the mechanical properties also highlight the potential of the addition of tin (Sn) in Mg alloy. It was reported by Alikawa and Taketani, that the inclusion of tin in the alloy contributes to an increase in the strength especially for the tensile yield strength [17]. This claim was also supported by Bakke and Westengen that concluded that Mg alloys with high Sn content effectively contribute to a gain in tensile strength that is above AZ91D couple with an increase in creep resistance [18]. Antimony (Sb) is another element that was investigated by Yuan et al. to evaluate its behaviour when combine into Mg alloy [19]. The authors observed that an addition of up to 0.35 wt. % of Sb results in a significant increase in both yield strength and creep resistance. On the other hand, a slight decrease of the alloy ductility was also noted. Furthermore, cerium (Ce) was another element that was subject to a study to observe the final microstructure of Mg alloy especially on AZ91. This study claim that a substantial grain refinement was noted when less than 1.0 wt. % of Ce was added to the alloy which also indicate an increased in tensile strength [20]. The effect of Bismuth (Bi) on the aging process on AZ91 alloy was evaluated by Yuan et al. and they concluded that the inclusion of Bi in Mg alloy tends to slowdown the aging process [21]. In addition, Drits et al. found out that Bi has a positive impact on the overall behaviour of Mg alloy in term of heat resistance at elevated temperature [22]. But a decrease in the strength properties was recorded when Bi was included to Mg-Nd alloys in both room temperature and at 250° C. The authors assume that this decrease in strength of Mg alloy can be connected to the decrease of the Nd solubility in Mg solid solution. In another study it was also noted that Ca, Li, Ba and Co have no effect on the tensile strength of Mg alloy [23].

### 2.1. Machinability

Magnesium alloy is among the types of material that has a good machining ability mainly due to its low hardness and modulus of elasticity. The cutting power recorded during machining operations such as sawing, punching, drilling, milling and turning for magnesium is low and the surface quality is exceptional. In addition, given the softness of magnesium alloys such as AZ 31 and AZ 91, the machining parameters such as the spindle speed can be set at an extremely high level. In addition, with a high thermal conductivity, the tool life is extended and stay sharp for a longer machining time [8]. In terms of power consumption, Figure 1 demonstrate that machining magnesium consume less power compare to other materials listed such as aluminium alloys or nickel alloys [24].

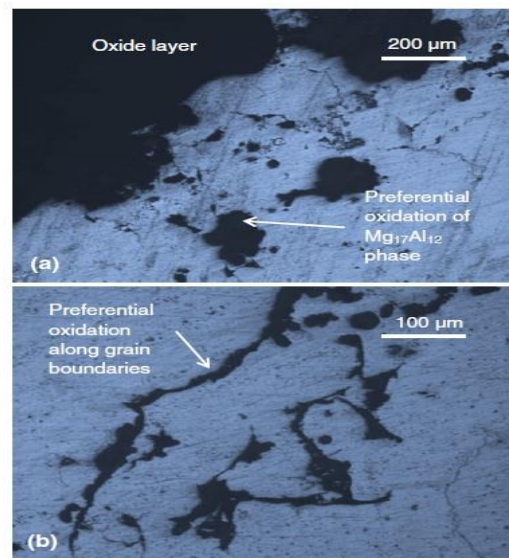


**Figure 1.** Values of specific power consumption for a variety of metals [24]

Moreover, with the less power requirements in the machining of magnesium alloys, a deeper cuts and higher feed rate are achievable thus creating a more efficient machining operation compare to other materials. Most of the machining operation relation to magnesium are done without any coolant but if necessary, a very light mineral oil is use and its highly recommended not to make use of any water-based coolant due to the risk of ignition. The most common cutting tools used for the machining of magnesium are high speed steel (HSS) or carbide tipped tools. It is also advisable to maintain a sharp cutting tool tip to prevent any unwanted rise of cutting temperature [24]. Moreover, other type of cutting tool such as diamond cutter was also experimented in machining of magnesium alloy and the results were quite promising but unfortunately the cost is relatively high. Next, milling operation using magnesium alloy as base material is very common but the cutting tool should have less teeth compare to standard tools so that the larger chips between the teeth will prevent a high degree of friction resulting in a lower cutting temperature. In addition, this specific type of cutting tool will also allow a higher cutting speed, lower power consumption and finally a better surface finish. To perform a smooth drilling operation on magnesium alloy, a twist drills made of High-speed steel is recommended. In addition, for Die threading of magnesium, a cutting-edge relief of 0.10 mm is generally suggested [24].

## 2.2. Microstructure

The microstructure of magnesium alloy was found by Czerwinski to be quite complex to understand due to its reaction to the environment that as a result form oxidation [25]. This author claim that the rate of oxidation is increase due to the additions of the alloying elements such as Zn, Sn, Ni, Cu, In, Ag, Cd, and Ti. However, a study suggests that the addition of some reactive element such as rare earth metals can decrease oxidation in magnesium alloy [26]



**Figure 2.** Effect of alloy phase composition on preferential oxidation at high temperatures: (a) subsurface oxidation; (b) selective oxidation of grain boundaries in AZ 91 [27]

Furthermore, in an experimental study on the evolution of oxidation of AZ 91 as shown in figure 2, the authors observe that the reaction of the alloy to oxidation is not dependent on the thickness of the scale but assume that oxygen can easily penetrate the metal surface and create oxidation. In addition, it was also reported that the oxidation is also directly related to the temperature as at a temperature of 430°C, a catastrophic oxidation was form. At this specific stage, the nodular growth is triggered by a different phase composition and inhomogeneity of the alloy which in the end create a liquid island of metal [27]. The nodular growth can also be prevented by the addition of rare earth material as stated earlier. As stated in in another findings, the rare earth ions tend to diffuse to native oxide grain boundaries and at the same time blocking the outward diffusion of metals cations. Therefore, an internal diffusion of oxygen ions is the only option for the oxidation to build-up. The thin-oxide layer form due to the reaction of Magnesium oxide (MgO) is not a permanent solution to prevent oxidation because they are very sensitive to environmental factors and may be subjected to severe damage. On the other hand, if the MgO is combine to a reactive element such as rare earth, it was reported that the magnesium alloy was given a better protection against the environment or even during in service in high temperature conditions [27].

### 3. Conclusion

The review on magnesium alloy briefly expose some of the key elements involve in the current manufacturing industries such as mechanical properties, microstructure, and machinability. All these elements are interrelated to each other starting from the chemical composition of the material where the control of the grain structure is very essential to achieve a required level of strength, ductility, and toughness. The control of the grain structure has been very successful in other material such as aluminium alloy, but more study is needed for magnesium alloy to be fully accepted by the manufacturing industries. In addition, the high probability of oxidation has also been discussed and much more study is needed to expand the application of magnesium alloy in other highly corrosive environment. Concerning the machinability of magnesium alloy, this review highlight that most machining operation are conducted in a smooth way by using the proper cutting tools and cutting parameters to prevent the risk of ignition that is very common when dealing with magnesium alloy.

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