

## BALLISTIC PERFORMANCE OF MAGNESIUM ALLOY AZ31B

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### ABSTRACT

Wrought magnesium alloys, which maintain various niche market applications due to their unique properties, have been the subject of a heightened level of research and development for potential application in the automotive market; however, little data is available on their ballistic properties. In order to fill this gap, the US Army Research Laboratory (ARL) and Magnesium Elektron North America, Incorporated (MENA) conducted a cooperative effort to evaluate magnesium alloy AZ31B, which was commercially available in a wrought form. MENA produced the rolled product and conducted the mechanical testing, while ARL performed the ballistic testing. Some limited ballistic data is provided for this alloy in both the H24 and O tempers.

### INTRODUCTION

Magnesium based alloys are of current interest to the United States military community because they represent the lightest of all structural metal alloys. The density of magnesium is approximately 35% lower than aluminum and approximately 77% lower than steel [1]. Moderate strength of commercially available wrought magnesium alloy plate, coupled with relatively low density, translates into a specific strength that is roughly equivalent with aluminum armor alloys as shown in Figure 1, where TUS and TYS represent the Tensile Ultimate Strength and Tensile Yield Strength respectively.

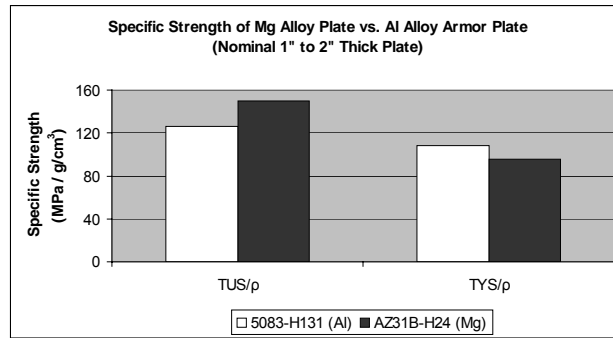


Figure 1. Specific Strength of Mg vs. Al Alloy Armor Plate [8]

Magnesium alloys also have a relatively low elastic modulus, E, compared to other metal alloys, which translates into a relatively high specific stiffness as shown in Figure 2. In general, there is a positive correlation between tensile strength and small arms

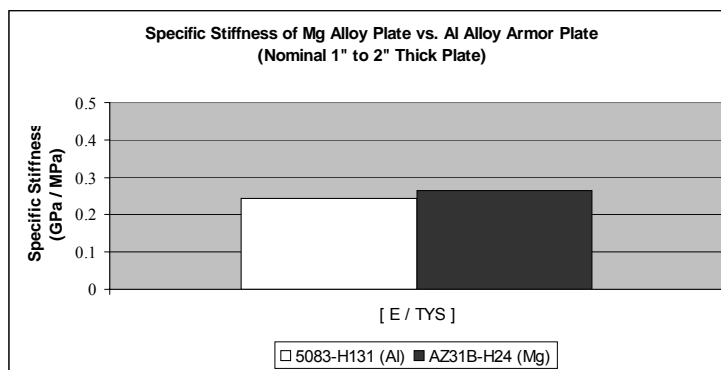


Figure 2. Specific Stiffness of Mg vs. Al Alloy Armor Plate [8]

ballistic performance in metal alloys; and, higher stiffness typically contributes to enhanced energy absorption upon ballistic impact; therefore, one would predict a possible benefit in wrought magnesium alloy armor applications. Table 1 provides comparative physical properties of some metal alloys of interest for armor applications [1].

TABLE 1. Selected metal alloy physical properties [1]

Base Metal	Metal Alloy	Density (g/cm <sup>3</sup> )	Elastic Modulus (GPa)	Specific Modulus (GPa/ g/cm <sup>3</sup> )
Magnesium	AZ31B	1.77	45	25.4
Aluminum	5083AL	2.66	70	26.3
Steel	'RHA'	7.83	205	26.1

Shock-mitigation through higher vibration damping capacity could translate into improved overall ballistic performance. Specific Damping Capacity (“SDC”) is a dimensionless value that can be used to compare various homogeneous materials. By definition, SDC is related to the “loss factor”  $N$  by eq. (1),

$$\text{SDC} = 2\pi N \quad (1)$$

where  $N$  is the ratio of energy dissipated during one cycle of harmonic stress to the maximum strain energy stored in the material during the cycle<sup>[2]</sup>. Table 2 provides Specific Damping Capacities for some metal alloys of interest<sup>[3]</sup>, which indicates that typical magnesium alloys can provide higher damping capacity over typical aluminum alloys and hardened steel.

Table 2. Specific Damping Capacity<sup>[3]</sup>

<b>Metal Alloy</b>	<b>SDC</b>
Typical Mg Alloys	0.4 – 1.6
Hardened Steel	0.2-1
Typical Aluminum Alloys	0.1-0.25

The desirable physical properties of magnesium alloys (i.e., low density and high damping capacity), coupled with respectable specific strength and stiffness relative to other engineering materials, is the impetus for this initial investigation into the ballistic properties of wrought magnesium alloys.

## **EXPERIMENTAL PROCEDURES**

Rolled plate from magnesium alloy AZ31B was selected for the subject ballistic characterization because rolled AZ31B plate is weldable, commercially available and is specified by several governing US bodies, including AMS and ASTM. Alloy-Temper combinations AZ31B-O and AZ31B-H24 were selected to identify any possible causal factors in ballistic performance in comparing the hot-rolled and fully annealed plate (-O condition) and the cold-rolled and partially annealed plate (-H24 condition).

The magnesium plate was alloyed, cast, rolled, thermally treated and tensile tested by Magnesium Elektron North America, Inc. (‘MENA’) in Madison, Illinois in accordance with aerospace specifications AMS 4375K (AZ31B-O) and AMS 4377H (AZ31B-H24). Chemical composition limits required by these specifications for alloy AZ31B are displayed in Table 3, and the actual tensile testing results are displayed in Table 4.

Table 3. Alloy AZ31B chemical composition limits (weight percent)

	Al	Zn	Mn	Si	Cu	Ca	Fe	Ni	Others Each	Others Total	Mg
Max	3.5	1.3	---	0.05	0.05	0.04	0.005	0.005	0.10	0.30	Balance
Min	2.5	0.7	0.20	---	---	---	---	---	---	---	

Ballistic threats were selected in a manner that would allow for direct comparison to other metal alloy armor standards, particularly to aluminum alloy armor plate standards. Several weldable aluminum alloys (e.g., AA5083 and AA7039) are

Table 4. Actual tensile properties for Mg alloy plates tested

Alloy-Temper	Plate Thickness (mm)	Tensile Properties		
		TUS (MPa)	TYS (MPa)	Elong (%)
AZ31B-O	7.62	254	153	21.5
	31.50	258	151	11.5
AZ31B-H24	7.75	265	179	19.0
	76.48	262	169	9.5

currently specified for use in vehicle armor systems<sup>[4,5]</sup>. The 0.30-cal armor-piercing projectile is a typical small arms threat used in ballistic testing because of its common employment worldwide. The fragments generated from improvised explosive devices (IED's) are current and highly lethal threats that come in a multitude of configurations based on the device design, and use of the fragment simulating projectile ('FSP') is the standard for developing armor that protects against fragment projectiles.

Ballistic testing of all magnesium alloy plate samples was performed by the United States Army Research Laboratory ('ARL') at Aberdeen Proving Grounds, Maryland in accordance with MIL-STD-662F, issued 18 December 1997. Ballistic results were characterized using the standard  $V_{50}$  test methodology, also documented in MIL-STD-662F.

The specific ballistic threats used to test the magnesium alloy plate samples were the 0.30-cal APM2 armor-piercing projectile<sup>[6]</sup>, depicted below in Figure 3, and the 0.22-cal, 0.50-cal and 20mm FSP fragment simulating projectiles designed in accordance with MIL-DTL-46593B (MR), issued 6 July 2006, as depicted below in Figure 4.

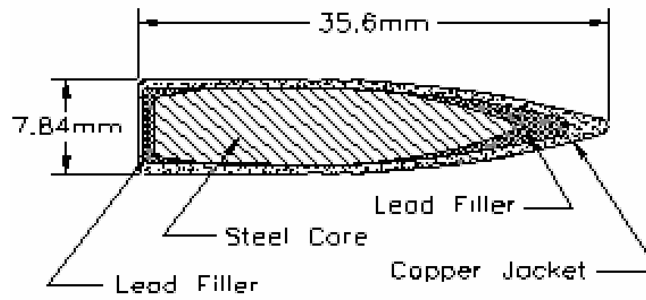


Figure 3. 0.30-cal APM2 Armor-Piercing Projectile

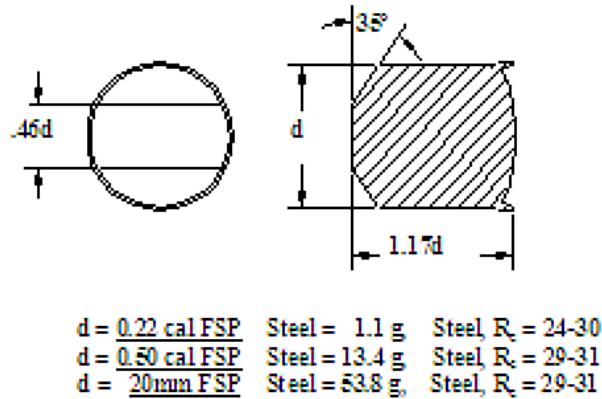


Figure 4. Fragment Simulating Projectile

## EXPERIMENTAL RESULTS

Table 5 compares the ballistic results for the AZ31B magnesium alloy plates with historical results for RHA and aluminum alloy 5083 in terms of equivalent areal densities (i.e., mass per unit surface area) and in terms of the actual plate thicknesses <sup>[7]</sup>.

Table 5: Ballistic Testing Results  
 (NOTE: RHA and AA5083-H131 are historical results provided by the ARL database)

0.30-cal APM2				0.22-cal FSP			
Alloy-Temper	Areal Density (kg/m <sup>2</sup> )	Plate Thickness (mm)	V50 (m/s)	Alloy-Temper	Areal Density (kg/m <sup>2</sup> )	Plate Thickness (mm)	V50 (m/s)
Steel (RHA)	~ 55.7	7.11	524	Steel (RHA)	~ 13.7	1.78	366
AA5083-H131		21.03	506	AA5083-H131		5.18	396
AZ31B-O		31.5	511	AZ31B-O		7.62	417
Steel (RHA)	~ 135.2	17.22	914	AZ31B-H24		7.75	421
AA5083-H131		50.93	853				
AZ31B-H24		76.48	863				
0.50-cal FSP				20mm FSP			
Alloy-Temper	Areal Density (kg/m <sup>2</sup> )	Plate Thickness (mm)	V50 (m/s)	Alloy-Temper	Areal Density (kg/m <sup>2</sup> )	Plate Thickness (mm)	V50 (m/s)
Steel (RHA)	~ 55.7	7.11	718	Steel (RHA)	~ 135.2	17.22	878
AA5083-H131		21.03	663	AA5083-H131		50.93	1125
AZ31B-O		31.5	639	AZ31B-H24		76.48	897

## CONCLUSIONS

Research and development of magnesium alloys for lightweight commercial applications has generated interest in the US military community for application in lightweight armor. Ballistic performance of the AZ31B magnesium alloy plate was quite comparable to that of 5083 aluminum, save the 20mm FSP performance, where it fell short by about 20 percent. In comparing the ballistic performance of the AZ31B to RHA, the results were threat-dependent as well as plate thickness dependent (i.e., where the magnesium plates out-performed RHA on the 0.22-cal and 20mm FSP, it fell short of the RHA performance on the 0.30-cal APM2 and the 0.50-cal FSP). Because the plate samples were limited in number, the only direct comparison between AZ31B-O and AZ31B-H24 was in the 0.22-cal FSP, where the performance was almost identical.

These results are encouraging, particularly because the magnesium alloy AZ31B was designed as a general purpose engineering alloy with moderate strength, good weldability and good corrosion resistance. By no means is AZ31B an alloy that has been optimized for ballistic performance, where higher strength without an appreciable loss in ductility would be highly desirable.

ARL and MENA are currently collaborating to generate a US military ballistic specification for AZ31B plate. Efforts are currently underway to analyze and understand the ballistic defeat mechanisms associated with magnesium alloys, and to

characterize ballistic performance of higher strength wrought magnesium alloys - including Magnesium Elektron's ultra-high strength experimental alloy Elektron 675.

## REFERENCES

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