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Ballistic Evaluation of Magnesium Alloy AZ31B

by Tyrone L. Jones, Richard D. DeLorme, Matthew S. Burkins,
and William A. Gooch

ARL-TR-4077 **April 2007**

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14. ABSTRACT

Wrought magnesium alloys, which maintain various niche market applications because of their unique properties, have been the subject of a heightened level of research and development for potential application in the automotive market; however, few data are available about their ballistic properties. In order to fill this gap, the U.S. Army Research Laboratory (ARL) and Magnesium Elektron North America (MENA), Inc., 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, and ARL performed the ballistic testing. Some limited ballistic data are provided for this alloy in both the H24 and O tempers.

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AZ31B; ballistic performance; magnesium

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1. 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*). The 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.

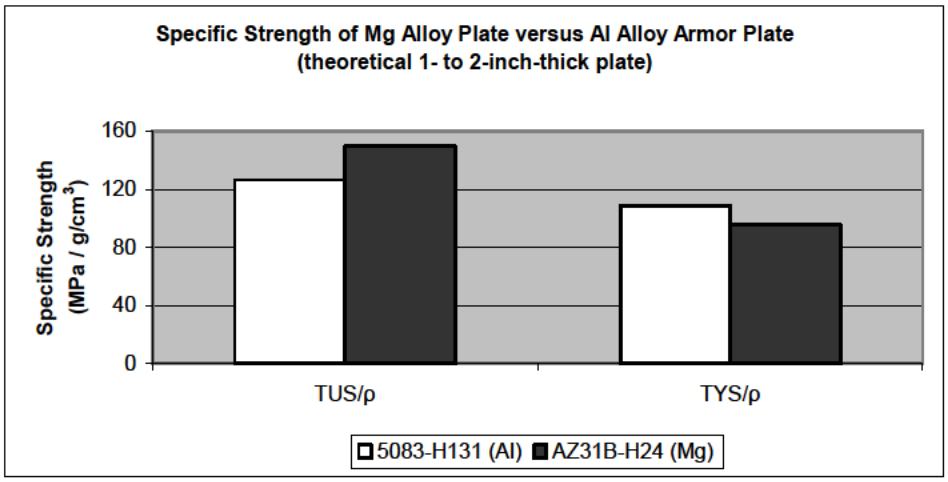

Figure 1. Specific strength of magnesium versus aluminum alloy armor plate (*2*).

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 ballistic performance in metal alloys. 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 (*2*).

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.

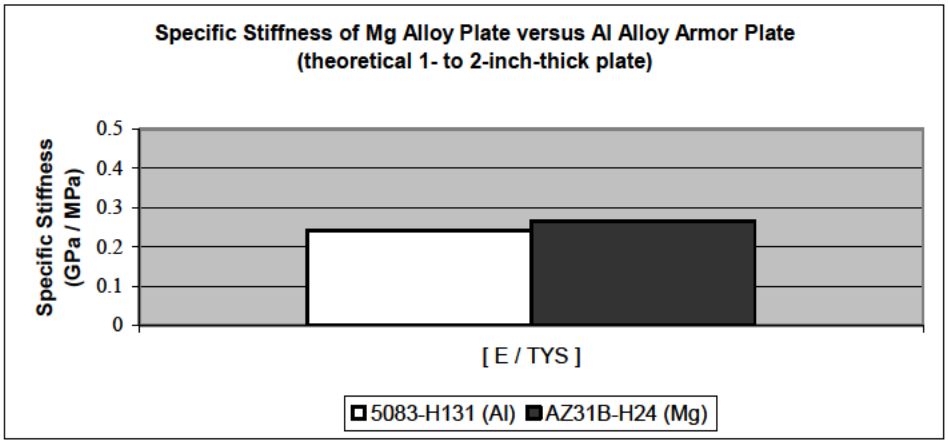

Figure 2. Specific stiffness of magnesium versus aluminum alloy armor plate (*2*).

Table 1. Selected metal alloy physical properties (*1*).

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

By definition, SDC is related to the "loss factor" N by equation 1:

$$SDC = 2\pi N \tag{1}$$

in which 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 (*3*). Table 2 provides SDCs for some metal alloys of interest (*2*), which indicates that typical magnesium alloys can provide higher damping capacity than typical aluminum alloys and hardened steel.

Table 2. Specific damping capacity (*2*).

Metal Alloy	SDC
Typical Mg Alloys	0.4 to 1.6
Hardened Steel	0.2 to 1
Typical Aluminum Alloys	0.1 to 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, are the impetus for this initial investigation into the ballistic properties of wrought magnesium alloys.

2. Experimental Procedures

Rolled plate from magnesium alloy AZ31B was selected for the subject ballistic characterization because AZ31B plate is weldable and commercially available and is specified by several governing U.S. bodies, including aerospace material specifications (AMS) and the American Society for Testing and Materials. Alloy-Temper combinations AZ31B-O and AZ31B-H24 were selected to identify any possible causal factors in ballistic performance in a comparison of 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 (MENA), Inc., 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 (*4*).

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

	Al	**Zn**	**Mn**	**Si**	**Cu**	**Ca**	**Fe**	**Ni**	**Other (Each)**	**Other (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	---	---	---	---	---	---	---	

Table 4. Actual tensile properties for magnesium alloy plates tested.

Alloy-Temper	**Plate Thickness (mm)**	**Tensile Properties**		
		TUS (MPa)	**TYS (MPa)**	**Elong (percent)**
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

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 currently specified for use in vehicle armor systems (*5*, *6*). The 0.30-cal (7.62 mm x 63) APM2 armor-piercing projectile is a typical small arms threat used in ballistic testing because worldwide. The fragments generated from improvised explosive devices (IEDs) 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 U.S. Army Research Laboratory (ARL) at Aberdeen Proving Ground, Maryland, in accordance with MIL-STD-662F, issued 18 December 1997 (*7*). Ballistic results were characterized with the use of 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 (*8*), the 0.50-cal APM2 armor-piercing projectile (*9*), depicted in figures 3 and 4, and the 0.22-cal, 0.50-cal, and 20-mm FSPs produced in accordance with MIL-DTL-46593B (MR), issued 6 July 2006, as depicted in figure 5.

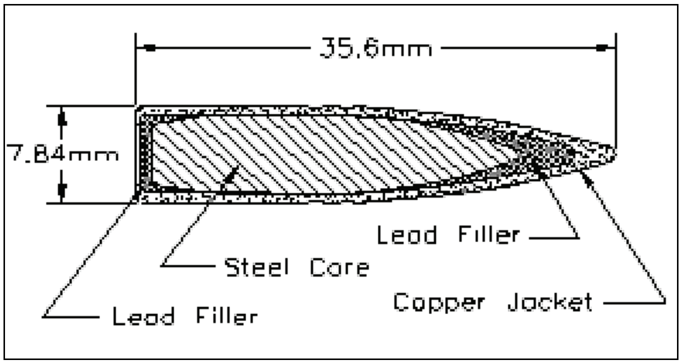

Figure 3. 0.30-cal APM2 armor-piercing projectile.

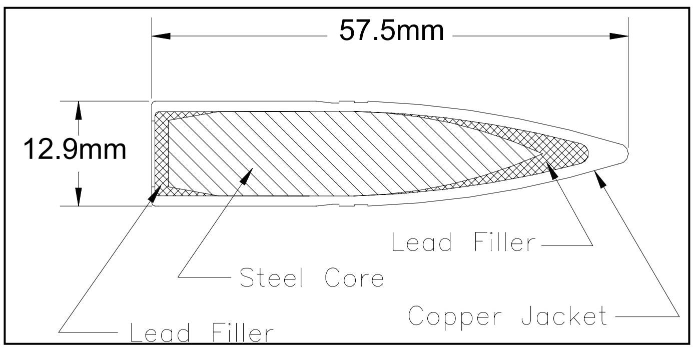

Figure 4. 0.50-cal APM2 armor-piercing projectile.

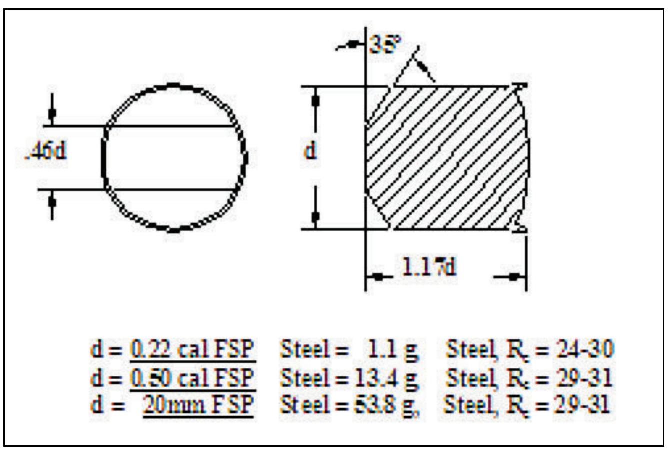

Figure 5. Fragment-simulating projectile.

3. Experimental Results

Table 5 compares the ballistic results for the AZ31B magnesium alloy plates with historical results for rolled homogenous armor (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 (*9*).

Table 5. Ballistic testing results.

0.30-cal APM2			
Alloy-Temper	Areal Density (kg/m^2)	Plate Thickness (mm)	V50 (m/s)
Steel (RHA)	~ 55.7	7.11	524
AA5083-H131		21.03	506
AZ31B-O		31.5	511
Steel (RHA)	~ 135.2	17.22	914
AA5083-H131		50.93	853
AZ31B-H24		76.48	863

0.22-cal FSP			
Alloy-Temper	Areal Density (kg/m^2)	Plate Thickness (mm)	V50 (m/s)
Steel (RHA)	~ 13.7	1.78	366
AA5083-H131		5.18	396
AZ31B-O		7.62	417
AZ31B-H24		7.75	421

0.50-cal FSP			
Alloy-Temper	Areal Density (kg/m^2)	Plate Thickness (mm)	V50 (m/s)
Steel (RHA)	~ 55.7	7.11	718
AA5083-H131		21.03	663
AZ31B-O		31.5	639

20mm FSP			
Alloy-Temper	Areal Density (kg/m^2)	Plate Thickness (mm)	V50 (m/s)
Steel (RHA)	~ 135.2	17.22	878
AA5083-H131		50.93	1125
AZ31B-H24		76.48	897

0.50-cal APM2			
Alloy-Temper	Areal Density (kg/m^2)	Plate Thickness (mm)	V50 (m/s)
Steel (RHA)	~ 135.2	17.22	649
AA5083-H131		50.93	626
AZ31B-O		76.48	649

(Note: RHA and AA5083-H131 are historical results provided by reference 2.)

4. Conclusions

Research and development of magnesium alloys for lightweight commercial applications has generated interest in the U.S. military community for application in lightweight armor. Ballistic performance of the AZ31B magnesium alloy plate was quite comparable to that of 5083 aluminum, except for the 20-mm FSP performance, where it fell short by about 20%. In comparing the ballistic performance of the AZ31B to RHA, we saw that the results were threat dependent as well as plate thickness dependent (i.e., where the magnesium plates out-performed RHA against the 0.22-cal and 20-mm FSP and matched the RHA performance against the 0.50-cal APM2; it fell short of the RHA performance against 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 U.S. military ballistic specification for AZ31B plate. Efforts are currently under way to analyze and understand the ballistic defeat mechanisms associated with magnesium alloys and to characterize ballistic performance of higher strength wrought magnesium alloys, including MENA's ultra-high strength experimental alloy Elektron 675.

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M SCHILDKNECHT
FISCHBACHSTRASSE 16
D 90552 ROTBENBACH AD
PEGNITZ
GERMANY

DYNAMEC RSCH AB
A PERSSON
PARADESGRND 7
SODERTALJE S151 36
SWEDEN

ETBS DSTI
P BARNIER M SALLES
ROUTE DE GUERAY
BOITE POSTALE 712
18015 BOURGES CEDEX
FRANCE

FEDERAL MINISTRY OF DEFENCE
DIR OF EQPT & TECH LAND
RUV 2
D HAUG
POSTFACH 1328
53003 BONN
GERMANY

FRANHOFER INSTITUT FUR
KURZZEITDYNAMIK
ERNST MACH INSTITUT
V HOHLER E STRASSBURGER
R TRAM K THOMA
ECKERSTRASSE 4
D 79 104 FREIBURG
GERMANY

MINISTRY OF DEFENCE
DGA/SPART
C CANNAVO
10 PLACE GEORGES CLEMENCEAU
BP 19
F 92211 SAINT CLOUD CEDEX
FRANCE

HIGH ENERGY DENSITY RSCH CTR
V FORTOV G KANEL
IZHORSKAY STR 13/19
MOSCOW 127412
RUSSIAN REPUBLIC

INGENIEURBURO DEISENROTH
F DEISENROTH
AUF DE HARDT 33 35
D 5204 LOHMAR 1
GERMANY

INST OF CHEMICAL PHYSICS
S RAZORENOV
142432 CHERNOGOLOVKA
MOSCOW REGION
RUSSIAN REPUBLIC

INST FOR PROBLEMS IN MATERIALS SCI
S FIRSTOV B GALANOV O GRIGORIEV
V KARTUZOV V KOVTUN Y MILMAN
V TREFILOV
3 KRHYZHANOVSKY STR
252142 KIEV 142
UKRAINE

INST FOR PROBLEMS
OF STRENGTH
G STEPANOV
TIMIRY AZEVSKAYA STR 2
252014 KIEV
UKRAINE

INST OF MECH ENGR PROBLEMS
V BULATOV D INDEITSEV
Y MESCHERYAKOV
BOLSHOY 61 VO
ST PETERSBURG 199178
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IOFFE PHYSICO TECH INST
E DROBYSHEVSKI A KOZHUSHKO
ST PETERSBURG 194021
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NATL DEFENCE HDQRTRS
PMO MRCV MAJ PACEY
PMO LAV A HODAK
OTTOWA ONTARIO KIA OK2
CANADA

OTO BREDA
M GUALCO
VIA VALDIOCCHI 15
I 19136 LA SPEZIA
ITALY

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M MAYSELESS Y PARTOM
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DIVISION OF MATERIALS
S J SAVAGE J ERIKSON
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CENTRE DE RECHERCHES
ET D'ETUDES D'ARCUEIL
D BOUVART C COTTENNOT
16 BIS AVENUE PRIEUR DE
LA COTE D'OR
F 94114 ARCUEIL CEDEX
FRANCE