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US Army Research Laboratory

Ballistic Characterization of the Scalability of Magnesium Alloy AMX602

by Tyrone L Jones, Katsuyoshi Kondoh, David Moore, Isamu Otsuka, Allan Annis, Hiroto Nakazawa, Yoshinori Ohori, Ryo Numasawa, and Masamichi Takahashi

NOTICES

Disclaimers

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by Tyrone L Jones
Weapons and Materials Research Directorate, ARL

Katsuyoshi Kondoh
Joining and Welding Research Institute, Osaka University, Osaka, Japan

David Moore and Allan Annis
Taber Extrusions, Russellville, AR

Isamu Otsuka and Ryo Numasawa
Epson Atmix, Aomori, Japan

Hiroto Nakazawa and Yoshinori Ohori
Pacific Sowa, Tokyo, Japan

Masamichi Takahashi
National Material LP, Elk Grove Village, IL

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Tyrone L Jones, Katsuyoshi Kondo, David Moore, Isamu Otsuka, Allan Annis, Hiroto Nakazawa, Yoshinori Ohori, Ryo Numasawa, and Masamichi Takahashi

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14. ABSTRACT

The US Army Research Laboratory (ARL) formed a collaborative partnership with Osaka University Joining and Welding Research Institute (JWRI), Taber Extrusions, Epson Atmix, Pacific Sowa, Kurimoto, and National Material LP to domestically reproduce and scale-up military-grade magnesium alloy AMX602 at the Taber Extrusions manufacturing facility in Gulfport, MS. AMX602 material was provided in the form of 38.1-mm (1.5-inch)-wide bars, 101.6-mm (4-inch)-wide plate, and 152.4-mm (6-in)-wide plate. ARL and JWRI conducted mechanical analysis and dynamic impact examination to evaluate the lateral dimension scale-up of AMX602. The results were parametrically analyzed and compared with conventionally processed AZ31B-H24 and AA5083-H131. Details of the scalability of the AMX602 alloy are provided.

15. SUBJECT TERMS

magnesium, AMX602, armor mechanisms, AZ31B, aluminum alloy 5083

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1. Introduction

The US Army Research Laboratory's (ARL's) ballistic analysis of magnesium (Mg) alloys over the last 8 years has led to an increased understanding of the material's failure mechanisms and relationship between Mg alloy strength and ductility requirements for lightweight armor applications.[1] While Mg alloys have been used for military structural applications since World War II, very little research has been done to improve its mediocre ballistic performance.[2] The highest strength commercial Mg alloy available in plate form, AZ31B (1.78 g/cm^3), has proven to be a very good substitute armor material for AA5083 (2.66 g/cm^3) against armor-piercing projectiles on an equal weight basis.[3] It is also an adequate substitute armor material against fragment simulating projectiles (FSPs) within an areal density range that is FSP dependent.[4] However, shearing and scabbing are dominant features during ballistic impact. The ballistic data generated by ARL were used to develop the first set of Mg alloy acceptance standards, MIL-DTL-323333 (MR), titled, "Armor Plate, Magnesium Alloy, AZ31B, Applique".[5] Ultimate tensile strength (UTS), tensile yield strength , ductility, and grain size are all important parameters in determining the ballistic performance of metals. The bulk material properties of AZ31B are shown in Table 1. Figure 1 correlates impact energy absorption (J) versus Mg armor alloy AZ31B grain size (µm).[6]

Table 1 Objective mechanical properties of Mg armor alloys

Mg Alloy	Ultimate Tensile Strength (MPa)	Tensile Yield Strength (MPa)	Elongation to Failure (%)
AZ31B[7]	245	150	7
New Mg Alloy	400	350	20

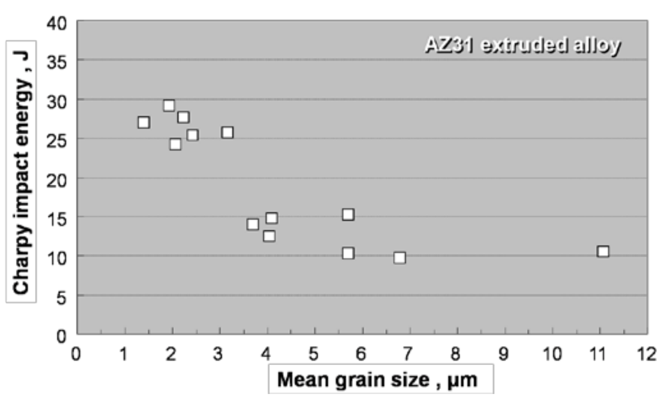


Fig. 1 AZ31B grain size vs. impact energy absorption

In 2009, ARL collaborated with the Joining and Welding Research Institute (JWRI) of Osaka University under contract through the International Technology Center-Pacific to develop and evaluate high-strength, high-ductility Mg alloy plate for structural applications that would exceed the ballistic performance of AA5083. Initial evaluation of conventionally rolled AZ31B plate versus powder-formed AZ31B plate showed that grain refinement is needed to significantly improve the viability of Mg armor alloy plate.[7]

New fundamental Mg alloying is needed to increase the impact energy and thus the performance of Mg alloy plates. The result showed a research opportunity to make Mg alloys viable armor materials that could compete with current aluminum (Al) armor alloy solutions.[4] Based on the preliminary material and ballistic analysis, the ARL/JWRI program set goals to develop Mg alloys with the mechanical properties shown on the lower row of Table 1.

Clearly, there were 2 potential paths forward toward achieving these set goals:

- Discover new chemical compositions to create high-strength, high-ductility Mg alloys, while not compromising the desirably low density of 1.78 g/cm^3.
- Improve grain refinement through novel processing techniques to produce high-strength, high-ductility Mg alloys.

As a result, ARL and JWRI collaboratively created 2 new experimental Mg alloys, AMX602 and ZAXE1711, in extruded 40-mm bars starting with an advanced metallurgical powder process. The successful ballistic and corrosion evaluation of each material[8] expanded our partnership into a coalition to reproduce and scale-up the lateral dimensions of AMX602 bars into 305- × 305-mm (12- × 12-inch) plates for commercial production in the United States. Cost was the driver in our selection of AMX602 over ZAXE1711. However, once scaling up of AMX602 is achieved, the same processing methodology can be applied to reproduce ZAXE1711. Details of the scale-up process and ballistic evaluation of AMX602 are discussed in the following sections.

2. Material Exploration

AMX602 (Mg-6Al-0.5Mn-2Ca by mass%) Mg alloy powders produced by the Spinning Water Atomization Process (SWAP) were used as raw input materials.[9,10] The coarse Mg alloy powders had particle dimensions of 1–5 mm. It was previously verified that the coarse Mg powders of these sizes were of low explosion risk. The α-Mg grain size of the raw powders was less than 0.5 µm. Powder compaction and hot extrusion were applied to these raw powders to fabricate the extruded bars. The bar had dimensions of 24.5 × 40 × 1,000 mm. Tensile test specimens machined from these bars were evaluated at room temperature. The material microstructures were observed using an optical microscope. The microstructural evaluation of ZAXE1711 is withheld from discussion until the patent application is processed.

3. Experimental Evaluation of Raw Materials

In SWAP powder preparation, schematically illustrated in Fig. 2a, noncombustive AMX602 Mg alloy ingots were melted at 1,053 K in a ceramic crucible covered by a protective inert gas. The molten metals were directly streamed inside the spinning water chamber from a crucible nozzle. Figure 3 shows the chemical composition of AMX602 alloy powders prepared by SWAP. The calcium is necessary because it reduces the combustive properties of the Mg alloys. The impurity content of iron and copper is controlled to less than 0.005% because they are known corrosive elements in Mg alloys. As shown in Fig. 2b, the size of the coarse AMX602 powders prepared by SWAP is approximately 1–4 mm, and they are of irregular shape. A cast ingot with the same composition was also prepared as a reference input material.

(a)

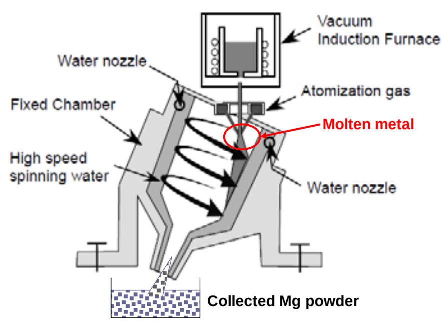


Illustration courtesy of Professor Kondoh, JWRI, Osaka University

(b)

Photo courtesy of Professor Kondoh, JWRI, Osaka University

Fig. 2 a) Schematic illustration of SWAP equipment to produce rapidly solidified Mg alloy powders; b) morphology of coarse Mg alloy powder prepared by SWAP

Al	Zn	Mn	Fe	Si	Cu	Ca	Mg
6.01	0.007	0.26	0.002	0.038	0.004	2.09	Bal.

Fig. 3 Chemical compositions of noncombustive Mg alloy powders

4. Powder Metallurgy

The powder was consolidated at room temperature using a 2,000-kN hydraulic press machine to fabricate the green compact. The green compact had a relative density of 85% and a 42-mm diameter. The columnar compact and cast ingot were heated at approximately 573–673 K for 180 s in an argon gas atmosphere, then immediately consolidated into full density material by hot extrusion. An extrusion ratio of 37 and an extrusion speed 1 m/s were used in this study.

5. Fabrication Procedure

Plate A and Plate B extrusions were performed on a 2,722-tonne (3,000-ton) press with a 279-mm (11-inch) container using a 25.4- × 101.6-mm (1- × 4-inch) die. The conditions are detailed in Table 2.

Table 2 Processing specifications of the Taber billets

Plate	A	B
Powder (kg)	25	27
Container temp (C)	427	427
Die temp (C)	426	427
Billet length (cm)	21.6	22.9
Nose billet temp (C)	333	296
Butt billet temp (C)	393	316
Extrusion speed (m/min)	2.44	1.52

The extrusion of Plate A had surface flaws. The cause was thought to be that the extrusion speed was too fast and the compaction too short. Hence, Plate B underwent a longer compaction time and a slower extrusion speed. The material surface and cross section of Plate B was greatly improved based on visual inspection of the extrusion.

Three experiments were conducted using 2 Kurimoto billets on the 1,633-tonne (1,800-ton) press with a 178-mm (7-inch) container to produce 25.4- × 101.6-mm (1- × 4-inch) plates, and then a 25.4- × 152.4-mm (1- × 6-inch) plate on the 2,722-tonne (3,000-ton) press with 279-mm (11-inch) container. Results are shown in Table 3. The material surface and cross section of Plate C, Plate D, and Plate E looked optically homogeneous. The material surface of Plate E had the best surface appearance.

Table 3 Processing specifications of the Kurimoto billets

Plate	C	D	E
Die Temp (C)	371	288	371
Billet Length (cm)	30.5	30.5	43.2
Nose Billet Temp (C)	316	260	288
Butt Billet Temp (C)	Not Measured	288	367
Extrusion Speed (m/min)	1.83	1.22	1.83

The extruded samples were sent to Osaka University for mechanical property measurement. The results will be discussed in the next section.

6. Mechanical Property Analysis

As mentioned earlier, all extruded plate-specimens were fabricated by using the mass-production equipment under various preheating and extrusion conditions. Figure 4 shows no cracking and fracture of the specimen surfaces. In addition, Fig. 5 indicates that the mean UTS values of the specimens were approximately 355–365 MPa, and the scatter was small. This mean value was almost same as that of the small-scale specimens fabricated in JWRI. Yield strength and elongation were also similar to those obtained at the smaller scale. This means that extrusion process was very stable and the mass-production process could be employed in consolidation of SWAP-Mg alloy powders.

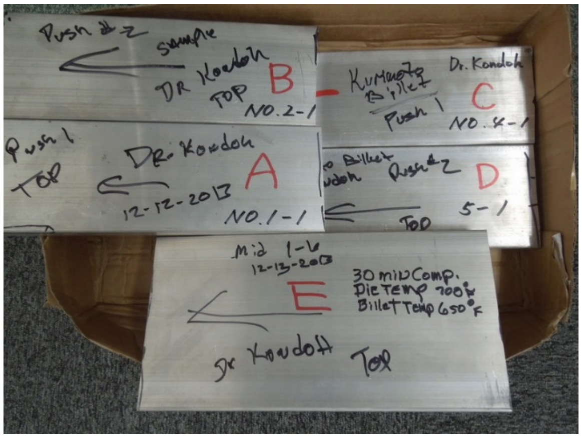


Fig. 4 Extruded Mg AMX602 plate

The extruded SWAP Mg alloy AMX602 was ballistically characterized for 38-mm (1.5-inch)-wide, 101.6-mm (4-inch)-wide, and (152.4-mm) 6-inch-wide plate.

The ballistic threat was selected in a manner that would allow for direct comparison to other metal alloy armor standards, particularly to the Al alloy 5083 (AA5083) armor plate standard. The weldable AA5083 is currently specified for use in many vehicle armor systems.[11] The test projectile selected was the 0.30-cal. FSP because it provides for quantifiable macro-mechanism features to be observed between Mg and Al alloys at the 45 kg/m^2 (9.2 pound per square foot) areal density range.

Ballistic testing of all Mg alloy plate samples was performed by ARL at Aberdeen Proving Grounds, MD, in accordance with MIL-STD-662F, issued 18 December 1997.[12] Ballistic results were characterized using the standard V_{50} test methodology, also documented in MIL-STD-662F.

7. Ballistic Experimental Procedures

The specific ballistic threat used to test the Mg alloy plate samples was the 0.30-cal FSP produced in accordance with MIL-DTL-46593B (MR), issued 6 July 2006, as depicted in Fig. 6.[13] The weight and hardness specifications are shown in Table 3.

L-Direction	(MPa)	(MPa)	(%)
	YS	UTS	Elongation
A-L direction	287.3	365.2	14.0
B-L direction	293.3	362.9	12.5
C-L direction	281.1	355.7	14.8
D-L direction	278.9	357.2	16.1
E-L direction	285.6	362.7	14.1

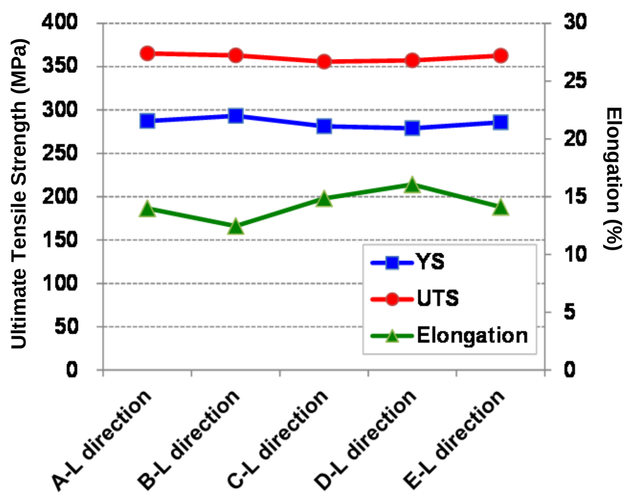
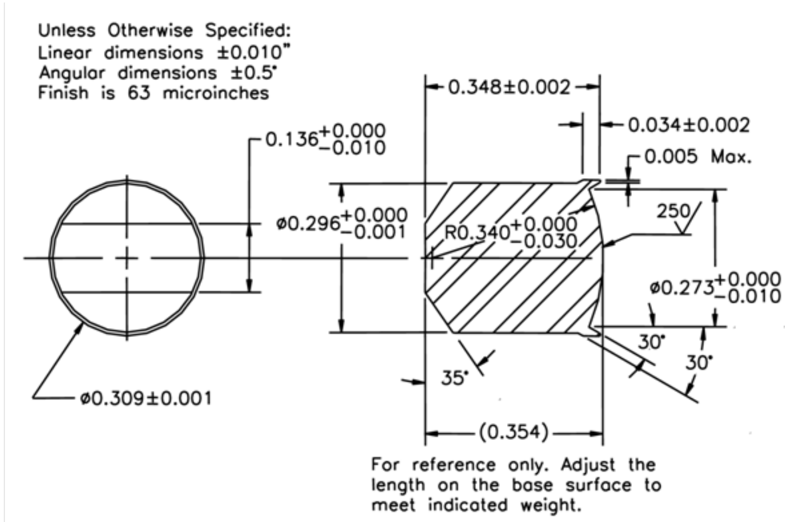


Fig. 5 Mechanical properties of extruded AMX602 plate



All Units Are in Inches.

Fig. 6 The 0.30-cal. FSP schematic diagram

FSP Type	Weight (g)	Rockwell Hardness C
0.30-cal.	2.9	30±2

Fig. 7 Projectile weight and hardness specifications

8. Ballistic Experimental Results

The raw experimental data from this study is provided in the Appendix. Table 4 compares the ballistic limits of the 38.1-mm-wide AMX602 bars manufactured at Taber Extrusions to 40-mm AMX602 bars manufactured by JWRI, ZAXE1711 bars manufactured by JWRI, AZ31B (reference material) manufactured by Magnesium Elektron North America, and AA5083 in terms of equivalent areal densities (i.e., mass per unit surface area) and in terms of the actual plate thicknesses. The AA5083 plate was evaluated in 2014. The V_{50} ballistic limits of samples B1 and B2 were estimated due to the limited material available. The hardness of the Mg plates was measured on a Brinell 500-kg scale, while the Al plate was measured on the 3,000-kg scale.

Table 4 V_{50} ballistic limits vs. the 0.30-cal FSP

Metal Alloys	Manufacturer	Plate Thickess	Plate Width	Hardness	Ballistic Limit
		mm	mm	HBN	m/s
AZ31B-H24	Mg-Elektron	25.400	304.8	61	843
AA5083 (2014)	--	17.04	304.8	99	1026
AMX602-1 (JWRI)	JWRI/KURIMOTO	25.190/25.235	40	80	1061
AMX602-2 (JWRI)	JWRI/KURIMOTO	25.171/25.210/25.197	40	80/80/83	1092
AMX602-3 (JWRI)	JWRI/KURIMOTO	25.171/25.178	40	80	1105
AMX602-B1 (Taber)	Taber Extrusions	25.489	38.1	99	1122
AMX602-B2 (Taber)	Taber Extrusions	25.483	38.1	99	1121
ZAXE1711-B (JWRI)	JWRI/KURIMOTO	25.248	40	80	1111
ZAXE1711-C (JWRI)	JWRI/KURIMOTO	25.229/25.241	40	77/83	1117
ZAXE1711-D (JWRI)	JWRI/KURIMOTO	25.210/25.279	40	80	1140

Figure 8 compares the reproduced 38.1-mm-wide AMX602 bars by Taber to the original 40-mm bars produced by JWRI. The performance of AMX602-B1 and AMX602-B2 are similar.

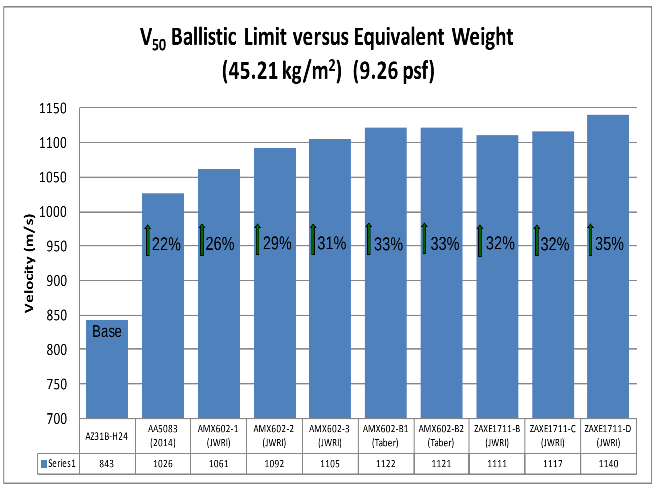


Fig. 8 Ballistic results of 38-mm-wide plate

The 38.1-mm-wide AMX602-B2 bar was evaluated again with the scaled-up AMX602 plates. The performance of 101.6-inch-wide AMX602 plates yielded the highest V_{50} ballistic limits as shown in Fig. 9. Figure 10 illustrates the damage of the 25.4- × 101.6-mm (1- × 4-inch) plate and the 25.4- × 152.4-mm (1- × 6-inch) plate.

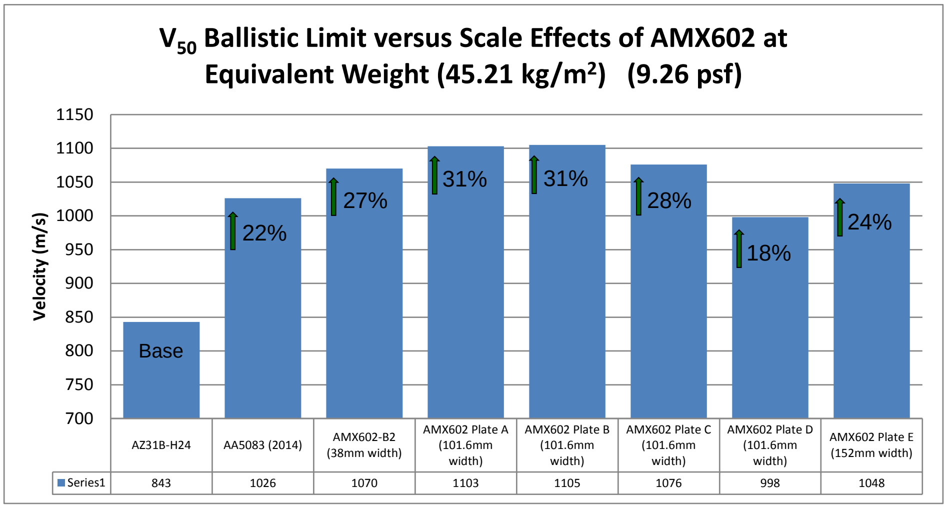
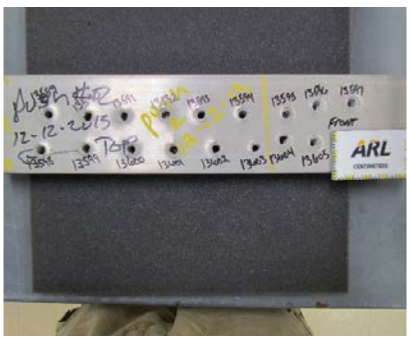


Fig. 9 Ballistic results of scaled-up plate



Entry of Impact - 25.4 mm × 101.6 mm
(1 inch × 4 inch)

Exit of Impact - 25.4 × 101.6 mm
(1 × 4 inch)

Entry of Impact - 25.4 x 152.4 mm
(1 × 6 inch)

Exit of Impact - 25.4 × 152.4 mm
(1 × 6 inch)

Fig. 10 Postballistic images of the AMX602 plates

9. Conclusions

Successful reproduction of the ballistic performance of AMX602 was achieved on widths from 38.1-mm-wide bars through 101.6-mm-wide plates produced by Taber. Overall, the AMX602 plates show an 18%–31% improvement over the performance of the baseline AZ31B Mg alloy. Based on the limited number of experimental data, the 152.4-mm plate produced a lower combination of ultimate strength and elongation properties than the 101.6-mm plates, resulting in up to a 7% reduction in a V_{50} ballistic limit. Still, the 152.4-mm plates provided enough of a deceleration mechanism to exceed the ballistic performance of the objective AA5083 plate by 2%. The anomaly is 101.6-mm Plate D, which showed no correlation between static properties and ballistic performance. A possible explanation may be the die temperature and billet temperature during the extrusion process were different for Plate D. Comparable penetration resistance across all the plates was observed. There was comparable localized damage for the 38.1-mm-wide bars through the 152.4-mm-wide plates of AMX602. The plates exhibited good scab containment at the back of the material. Plate A revealed good mechanical properties, especially good ductility. Scaling up to 305-mm-wide bars would be a logical next step based on the performance of the 152.4-mm-wide plate of AMX602. Future research should focus on understanding how to further improve strength without reducing ductility.

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Appendix. Raw Ballistic Data

This appendix appears in its original form, without editorial change.

Target:	**Magnesium AZ31B-H24**				**21-Feb-08**	
Plate #:	**--**				**EF106**	
Lot#:	--					
Thickness:	**24.968mm**	**0.983**	**"**			
Hardness:	**61 BHN on 500kg scale**					
Obliquity:	**0°**					
Projectile:	**.30 cal FSP**		Weight:	**44**	**grains**	
V50:	**843**	**m/s**		**# shots:**	**4**	
Std Dev:	**8**	**m/s**		**Spread:**	**18**	**m/s**
ZMR:	**0**					
Striking	Pitch	Yaw	Result	Used	Comments	Shot
Velocity				for V50		#
(m/s)	(deg)	(deg)	(PP/CP)			
845	**--**	**--**	**CP**	**Y**	**--**	**6720**
no chrono	--	--	PP	N	--	6721
838	**--**	**--**	**PP**	**Y**	**--**	**6722**
834	--	--	PP	N	--	6723
835	**--**	**--**	**PP**	**Y**	**--**	**6724**
871	--	--	CP	N	--	6725
853	**--**	**--**	**CP**	**Y**	**--**	**6726**

Target:	**AA5083-H131**				**16-Jun-14**		
					EF106		
Plate ID:	**--**						
Thickness:	**Plate**	**0.671**	**"**	**17.050**	**mm**		

Hardness:	**99 BHN on 3000kg scale**						
Obliquity:	**0°**						
Projectile:	**0.30-cal FSP**		Weight:	**44**	**grains**		
Velocity Measurement:			**Chrono**				
Low CP:	**1019**	**m/s**		**Low CP:**	**3342**	**ft/s**	
High PP:	**1027**	**m/s**		**High PP:**	**3368**	**ft/s**	
V50:	**1026**	**m/s**		**V50:**	**3365**	**ft/s**	
Std Dev:	**8**	**m/s**		**Std Dev:**	**26**	**ft/s**	
ZMR:	**8**	**m/s**		**ZMR:**	**26**	**ft/s**	
# shots:	**4**			**# shots:**	**4**		
Spread:	**18**	**m/s**		**Spread:**	**58**	**ft/s**	

Striking Velocity (ft/s)	Striking Velocity (m/s)	Pitch (deg)	Yaw (deg)	Result (PP/CP)	Used for V50	Comments	Shot #
3780	1152	--	--	CP	N	--	13626
3511	1070	--	--	CP	N	--	13627
3368	**1027**	**--**	**--**	**PP**	**Y**	**--**	**13628**
3464	1056	--	--	CP	N	--	13629
3433	1046	--	--	CP	N	--	13630
3400	**1036**	**--**	**--**	**CP**	**Y**	**--**	**13631**
3302	1006	--	--	PP	N	--	13632
3350	**1021**	**--**	**--**	**PP**	**Y**	**--**	**13633**
3342	**1019**	**--**	**--**	**CP**	**Y**	**--**	**13634**

Target:	**Mg Plate AMX602**				**20-May-14**		
Taber Extrusions Reproduction of Mg AMX602 bars from JWRI - Feb 2013							
Temper:	**602°C - 630°C**				**EF106**		
Plate ID:	**B2**						
Thickness:	**Bar**	**1.007**	**"**	**25.565**	**mm**		
Width:	**Bar**	**1.500**	**"**	**38.100**	**mm**		

Hardness:	**86 BHN on 500kg scale**						
Obliquity:	**0°**						
Projectile:	**0.30-cal FSP**		Weight:	**44**	**grains**		
Velocity Measurement:			**Chrono**				
Low CP:	**1070**	**m/s**		**Low CP:**	**3512**	**ft/s**	
High PP:	**1070**	**m/s**		**High PP:**	**3512**	**ft/s**	
V50:	**1070**	**m/s**		**V50:**	**3510**	**ft/s**	
Std Dev:	**2**	**m/s**		**Std Dev:**	**8**	**ft/s**	
ZMR:	**0**	**m/s**		**ZMR:**	**0**	**ft/s**	
# shots:	**4**			**# shots:**	**4**		
Spread:	**6**	**m/s**		**Spread:**	**19**	**ft/s**	

Striking Velocity (ft/s)	Striking Velocity (m/s)	Pitch (deg)	Yaw (deg)	Result (PP/CP)	Used for V50	Comments	Shot #
3517	**1072**	**--**	**--**	**CP**	**Y**	**--**	**13559**
3423	1043	--	--	PP	N	--	13560
3414	1041	--	--	PP	N	--	13561
3422	1043	--	--	PP	N	--	13562
3498	**1066**	**--**	**--**	**PP**	**Y**	**Ran out of Bar 1**	**13563**
3416	1041	--	--	PP	N	Start on Bar 2	13564
3512	**1070**	**--**	**--**	**PP**	**Y**	**--**	**13565**
3512	**1070**	**--**	**--**	**CP**	**Y**	**--**	**13566**

Target:	**Mg Plate AMX602**				**21-May-14**		
Taber Extrusions Reproduction of Mg AMX602 bars from JWRI - Dec 12, 2013							
					EF106		
Plate ID:	**Push 1**						
Thickness:	**Plate**	**0.996**	**"**	**25.286**	**mm**		
Width:	**Plate**	**1.500**	**"**	**38.100**	**mm**		

Hardness:	**77 BHN on 500kg scale**						
Obliquity:	**0°**						
Projectile:	**0.30-cal FSP**		Weight:	**44**	**grains**		
Velocity Measurement:			**Chrono**				
Low CP:	**1111**	**m/s**		**Low CP:**	**3646**	**ft/s**	
High PP:	**1098**	**m/s**		**High PP:**	**3601**	**ft/s**	
V50:	**1103**	**m/s**		**V50:**	**3617**	**ft/s**	
Std Dev:	**12**	**m/s**		**Std Dev:**	**38**	**ft/s**	
ZMR:	**0**	**m/s**		**ZMR:**	**0**	**ft/s**	
# shots:	**4**			**# shots:**	**6**		
Spread:	**26**	**m/s**		**Spread:**	**84**	**ft/s**	
Striking Velocity (ft/s)	Striking Velocity (m/s)	Pitch (deg)	Yaw (deg)	Result (PP/CP)	Used for V50	Comments	Shot #
3526	1075	--	--	PP	N	--	13567
3355	1023	--	--	PP	N	--	13568
3528	1075	--	--	PP	N	--	13569
3466	1056	--	--	PP	N	--	13570
3542	1080	--	--	PP	N	--	13571
3560	1085	--	--	PP	N	--	13572
3601	**1098**	**--**	**--**	**PP**	**Y**	**--**	**13573**
3704	1129	--	--	CP	N	--	13574
3707	1130	--	--	CP	N	--	13575
3651	**1113**	**--**	**--**	**CP**	**Y**	--	**13576**
3646	**1111**	**--**	**--**	**CP**	**Y**	--	**13577**
3656	**1114**	**--**	**--**	**CP**	**Y**	--	**13578**
3536	1078	--	--	PP	**N**	--	13579
3578	**1091**	**--**	**--**	**PP**	**Y**	--	**13580**
3572	**1089**	**--**	**--**	**PP**	**Y**	--	**13581**

Target:	**Mg Plate AMX602**				**4-Jun-14**		
Taber Extrusions Reproduction of Mg AMX602 bars from JWRI - Dec 12, 2013							
					EF106		
Plate ID:	**Push 1**						
Thickness:	**Plate**	**0.997**	**"**	**25.317**	**mm**		
Width:	**Plate**	**4.000**	**"**	**101.600**	**mm**		

Hardness:	**83 BHN on 500kg scale**						
Obliquity:	**0°**						
Projectile:	**0.30-cal FSP**		Weight:	**44**	**grains**		
Velocity Measurement:			**Chrono**				
Low CP:	**1101**	**m/s**		**Low CP:**	**3611**	**ft/s**	
High PP:	**1127**	**m/s**		**High PP:**	**3698**	**ft/s**	
V50:	**1105**	**m/s**		**V50:**	**3624**	**ft/s**	
Std Dev:	**18**	**m/s**		**Std Dev:**	**57**	**ft/s**	
ZMR:	**27**	**m/s**		**ZMR:**	**87**	**ft/s**	
# shots:	**10**			**# shots:**	**10**		
Spread:	**48**	**m/s**		**Spread:**	**158**	**ft/s**	
Striking	Striking	Pitch	Yaw	Result	Used	Comments	Shot
Velocity	Velocity				for V50		#
(ft/s)	(m/s)	(deg)	(deg)	(PP/CP)			
3522	1074	--	--	PP	N	--	13589
3481	1061	--	--	PP	N	--	13590
3534	1077	--	--	PP	N	--	13591
3547	**1081**	**--**	**--**	**PP**	**Y**	**--**	**13592**
3618	**1103**	**--**	**--**	**PP**	**Y**	**--**	**13593**
3566	**1087**	**--**	**--**	**PP**	**Y**	**--**	**13594**
3698	**1127**	**--**	**--**	**PP**	**Y**	**--**	**13595**
3668	**1118**	**--**	**--**	**CP**	**Y**	**--**	**13596**
3705	1129	--	--	CP	N	--	13597
3646	**1111**	**--**	**--**	**CP**	**Y**	**--**	**13598**
3494	1065	--	--	PP	N	--	13599
3716	1133	--	--	CP	N	--	13600
3540	**1079**	**--**	**--**	**PP**	**Y**	**--**	**13601**
3660	**1116**	**--**	**--**	**CP**	**Y**	**--**	**13602**
3611	**1101**	**--**	**--**	**CP**	**Y**	**--**	**13603**
3707	1130	--	--	CP	N	--	13604
3687	**1124**	**--**	**--**	**CP**	**Y**	**--**	**13605**

Target:	**Mg Plate AMX602**				**2-Jun-14**		
Taber Extrusions Reproduction of Mg AMX602 bars from JWRI - Dec 13, 2013							
					EF106		
Plate ID:	**Push 2**						
Thickness:	**Plate**	**1.00**	**"**	**25.40**	**mm**		
Width:	**Plate**	**4.00**	**"**	**101.60**	**mm**		

Hardness:	**77 BHN on 500kg scale**						
Obliquity:	**0°**						
Projectile:	**0.30-cal FSP**		Weight:	**44**	**grains**		
Velocity Measurement:			**Chrono**				
Low CP:	**1051**	**m/s**		**Low CP:**	**3448**	**ft/s**	
High PP:	**1101**	**m/s**		**High PP:**	**3611**	**ft/s**	
V50:	**1076**	**m/s**		**V50:**	**3530**	**ft/s**	
Std Dev:	**35**	**m/s**		**Std Dev:**	**115**	**ft/s**	
ZMR:	**50**	**m/s**		**ZMR:**	**163**	**ft/s**	
# shots:	**2**			**# shots:**	**2**		
Spread:	**50**	**m/s**		**Spread:**	**163**	**ft/s**	
Striking	Striking	Pitch	Yaw	Result	Used	Comments	Shot
Velocity	Velocity				for V50		#
(ft/s)	(m/s)	(deg)	(deg)	(PP/CP)			
3611	**1101**	**--**	**--**	**PP**	**Y**	**--**	**13582**
3557	1084	--	--	PP	N	--	13583
3554	1083	--	--	PP	N	--	13584
3555	1084	--	--	PP	N	--	13585
3426	1044	--	--	PP	N	--	13586
3359	1024	--	--	PP	N	--	13587
3448	**1051**	**--**	**--**	**CP**	**Y**	**--**	**13588**
						Testing Halted; Ran out of bar	

Target:	**Mg Plate AMX602**			**10-Jun-14**			
Taber Extrusions Reproduction of Mg AMX602 bars from JWRI - Dec 13, 2013							
				EF106			
Plate ID:	**Push 2**						
Thickness:	**Plate**	**0.995**	**"**	**25.267**	**mm**		
Width:	**Plate**	**4.000**	**"**	**101.600**	**mm**		

Hardness:	**72 BHN on 500kg scale**						
Obliquity:	**0°**						
Projectile:	**0.30-cal FSP**		Weight:	**44**	**grains**		
Velocity Measurement:			**Chrono**				
Low CP:	**1008**	**m/s**		**Low CP:**	**3308**	**ft/s**	
High PP:	**992**	**m/s**		**High PP:**	**3255**	**ft/s**	
V50:	**998**	**m/s**		**V50:**	**3273**	**ft/s**	
Std Dev:	**14**	**m/s**		**Std Dev:**	**47**	**ft/s**	
ZMR:	**0**	**m/s**		**ZMR:**	**0**	**ft/s**	
# shots:	**4**			**# shots:**	**4**		
Spread:	**30**	**m/s**		**Spread:**	**100**	**ft/s**	
Striking Velocity (ft/s)	Striking Velocity (m/s)	Pitch (deg)	Yaw (deg)	Result (PP/CP)	Used for V50	Comments	Shot #
3667	1118	--	--	CP	N	--	13606
3665	1117	--	--	CP	N	--	13607
3519	1073	--	--	CP	N	--	13608
3577	1090	--	--	CP	N	--	13609
3483	1062	--	--	CP	N	--	13610
3425	1044	--	--	CP	N	--	13611
3373	1028	--	--	CP	N	--	13612
3324	1013	--	--	CP	N	--	13613
3314	**1010**	**--**	**--**	**CP**	**Y**	**--**	**13614**
3154	961	--	--	PP	N	--	13615
3255	**992**	**--**	**--**	**PP**	**Y**	**--**	**13616**
3165	965	--	--	PP	N	--	13617
3163	964	--	--	PP	N	--	13618
3214	**980**	**--**	**--**	**PP**	**Y**	**--**	**13620**
3404	1038	--	--	CP	N	--	13621
3371	1027	--	--	CP	N	--	13622
3352	1022	--	--	CP	N	--	13623
3352	1022	--	--	CP	N	--	13624
3308	**1008**	--	--	**CP**	**Y**	--	**13625**
						Testing Halted; Ran out of bar	

Target:	**Mg Plate AMX602**				**13-May-14**		
Taber Extrusions Reproduction of Mg AMX602 bars from JWRI - Dec 13, 2013							
					EF106		
Plate ID:	**Push 3**						
Thickness:	**Plate**	**0.993**	**"**	**25.229**	**mm**		
Width:	**Plate**	**6.000**	**"**	**152.400**	**mm**		

Hardness:	**83 BHN on 500kg scale**						
Obliquity:	**0°**						
Projectile:	**0.30-cal FSP**		Weight:	**44**	**grains**		
Velocity Measurement:			**Chrono**				
Low CP:	**1033**	**m/s**		**Low CP:**	**3388**	**ft/s**	
High PP:	**1056**	**m/s**		**High PP:**	**3466**	**ft/s**	
V50:	**1048**	**m/s**		**V50:**	**3438**	**ft/s**	
Std Dev:	**10**	**m/s**		**Std Dev:**	**32**	**ft/s**	
ZMR:	**24**	**m/s**		**ZMR:**	**78**	**ft/s**	
# shots:	**6**			**# shots:**	**6**		
Spread:	**26**	**m/s**		**Spread:**	**86**	**ft/s**	
Striking Velocity (ft/s)	Striking Velocity (m/s)	Pitch (deg)	Yaw (deg)	Result (PP/CP)	Used for V50	Comments	Shot #
3635	1108	--	--	CP	N	--	13546
3388	**1033**	**--**	**--**	**CP**	**Y**	**--**	**13547**
3333	1016	--	--	CP	N	--	13548
3417	**1042**	**--**	**--**	**CP**	**Y**	**--**	**13549**
3349	1021	--	--	CP	N	--	13550
3331	1015	--	--	CP	N	--	13551
3371	1027	--	--	CP	N	--	13552
3501	1067	--	--	CP	N	--	13553
3474	**1059**	**--**	**--**	**CP**	**Y**	**--**	**13554**
3373	1028	--	--	PP	N	--	13555
3449	**1051**	**--**	**--**	**PP**	**Y**	**--**	**13556**
3466	**1056**	**--**	**--**	**PP**	**Y**	**--**	**13557**
3435	**1047**	**--**	**--**	**PP**	**Y**	**--**	**13558**

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List of Symbols, Abbreviations, and Acronyms

Al	aluminum
ARL	US Army Research Laboratory
FSP	fragment simulating projectile
JWRI	Joining and Welding Research Institute
Mg	magnesium
SWAP	Spinning Water Atomization Process
UTS	Ultimate tensile strength

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