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Initial Evaluation of Advanced Powder Metallurgy Magnesium Alloys for Dynamic Applications

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Abstract

The U.S. Army Research Laboratory (ARL) is interested in assessing the performance of different magnesium alloys. The ARL and the Joining and Welding Research Institute (JWRI) conducted a joint effort to develop and evaluate advanced powder metallurgy magnesium alloys AZ31B and AMX602 (Mg-6Al-0.5Mn-2Ca/mass%) sheets. JWRI performed the mechanical and metallurgical analysis, while ARL performed the ballistic analysis. The thin gauge magnesium alloy sheets were ballistically evaluated against the 0.22-cal fragment simulating projectile (FSP). The powder magnesium alloys' mechanical properties and ballistic performance are compared to the conventionally processed AZ31B-H24.

Introduction

The ballistic evaluation of conventionally rolled AZ31B-H24 plate has given the armor community a baseline of how it compares to 5083-H131AL aluminum alloy [1]. Powder metallurgy (P/M) process is effective to control the microstructure by refining grains and intermetallics, and producing non-equilibrium alloy compositions of metals [2]. In particular, rapid solidification process by atomization is often used to prepare raw powders with ultra-fine microstructures. In this study, a water-atomization process is applied to produce coarse magnesium alloy powders with fine grains and intermetallic compounds [3]. They are consolidated by the conventional P/M process such as cold compaction, spark plasma sintering, and hot extrusion process. The microstructures, static and ballistic properties of P/M wrought magnesium alloys are evaluated, and the effects of alloy elements and microstructures on their properties are discussed in detail.

Powder Metallurgy

Two kinds of magnesium alloy powder produced by water-atomization process were prepared in this study; AZ31B (Mg-3Al-1Zn-0.3Mn/mass%) and AMX602 (Mg-6Al-0.5Mn-2Ca/mass%) [4] coarse powders. The powder size of each grain was 1~4-mm as shown in Figure 1 to reduce the potential of the magnesium catching fire. They were compacted by applying 300 MPa at room temperature. The relative density of the green compact with 94-mm diameter of AZ31B and AMX602 was 92% and 90 %, respectively. On the other hand, each powder was supplied to spark plasma sintering (SPS) process [5] to accelerate the metallurgical bonding between powders. In SPS process, the raw powder was filled up into the carbon die with a diameter of 95-mm. The temperature was controlled at 473K in vacuum less than 4 Pa, and consolidation pressure of 10 MPa was applied during sintering in 1.8 ks.

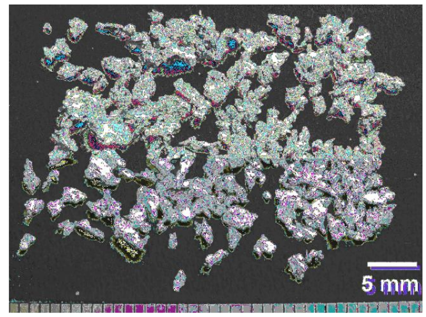

Figure 1. AZ31B and AMX602 Powder Size

The relative density of the SPS compact of AZ31B and AMX602 was 72% and 70 %, respectively. Each compact was heated at 573K, 598K, and 623K, and immediately processed by hot extrusion. The extrusion ratio and speed was 40 and 50 mm/s, respectively. The plate specimen with 40 mm width and 5 mm thickness was obtained by hot extrusion.

Mechanical Properties

Figure 2 indicates optical microstructures of AMX602 raw materials; atomized fine (a) and coarse powders (b), machined chips (c), and cast ingot (d). Fine powder (a) reveals small dendrite structures formed by rapid solidification. On the other hand, coarse powder shows larger grains than those of powder (a) due to the smaller solidification ration during atomization. Compared to machined chips (c) and cast material (d), they have the almost same grain size of 60~150 μ m, and some intermetallic compounds are observed at their grain boundaries.

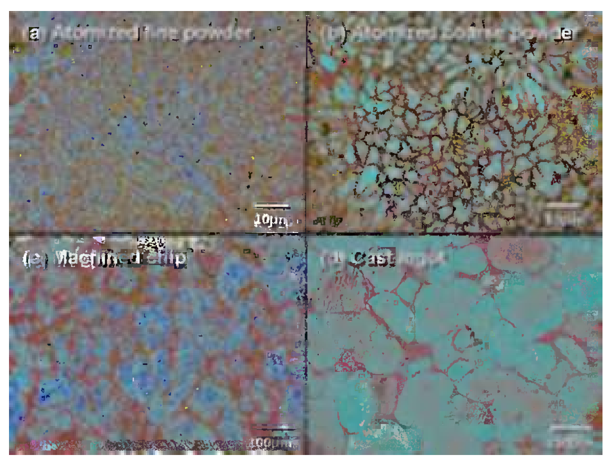
Figure 2 (a)-(d). Optical Microstructures of AMX602

In particular, the former has a lot of twinning induced by machining. Figure 3 shows XRD patterns of AMX602 wrought alloys extruded at 573K and 673K, when using atomized powder compacts (a) and cast ingot (b). Their microstructure observed by

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14. ABSTRACT
The U.S. Army Research Laboratory (ARL) is interested in assessing the performance of different magnesium alloys. The ARL and the Joining and Welding Research Institute (JWRI) conducted a joint effort to develop and evaluate advanced powder metallurgy magnesium alloys AZ31B and AMX602 (Mg-6Al- 0.5Mn-2Ca/mass%) sheets. JWRI performed the mechanical and metallurgical analysis, while ARL performed the ballistic analysis. The thin gauge magnesium alloy sheets were ballistically evaluated against the 0.22-cal fragment simulating projectile (FSP). The powder magnesium alloys? mechanical properties and ballistic performance are compared to the conventionally processed AZ31B-H24.

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SEM are shown In Figure 4, where (a) and (b) indicate the powder compacts and cast ingot, respectively. When employing atomized powders, the fine grains via dynamic recrystallization are observed. The lower extrusion temperature at 573K is effective to form the finer microstructures with a mean grains size of 0.45-micomemeters, which is measured by applying the image scanning soft ware to the SEM photo. Very fine white particles are Al_2Ca compounds precipitated during heating before hot extrusion.

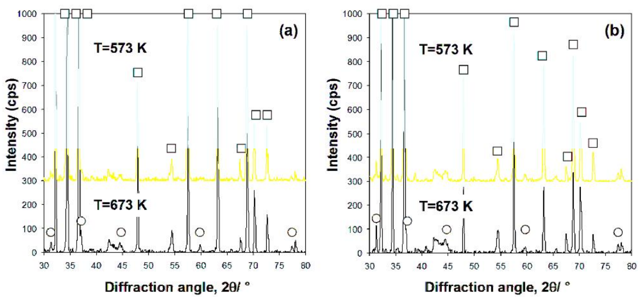

Figure 3. X-Ray Diffractions of AMX602: atomized powder compacts (a) & cast ingot (b)

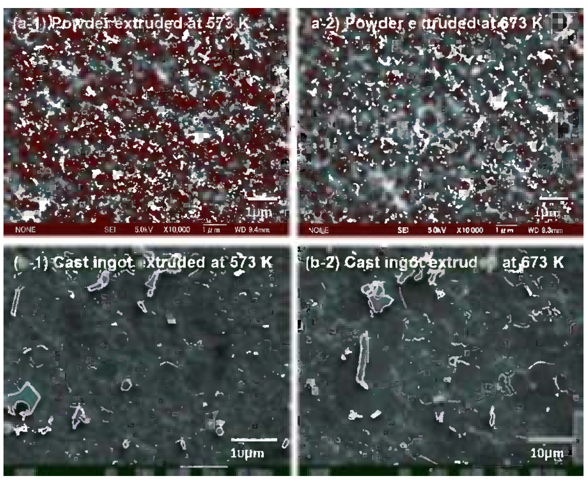

Figure 4. Scanning Electron Microscope of AMX602

In the case of cast ingots (b), the mean grain size of extruded materials at 573 K and 673 K is 1.96 μ m and 3.29 μ m, respectively. The higher heating temperature causes the grain coarsening. Both wrought alloys using AMX602 cast ingots contain coarse intermetallics as well. As shown in Figure 5, SEM-EDS analysis results on the specimen (b-1) indicate the intermetallic dispersoids are mainly Al_2Ca compounds, and exist at grain boundaries. The other results obviously show Al-Mn compounds with spherical shapes.

Both intermetallics are typical of the conventional AMX602 cast ingot. Micro Vicker's hardness of each material is as follows; 113 Hv (a-1), 94.3 Hv (a-2), 77.0 Hv (b-1), and 69.9 Hv (b-2). The hardness of wrought alloys using atomized powder compacts is higher than that using the cast ingot, and shows a remarkable dependence on the grain size.

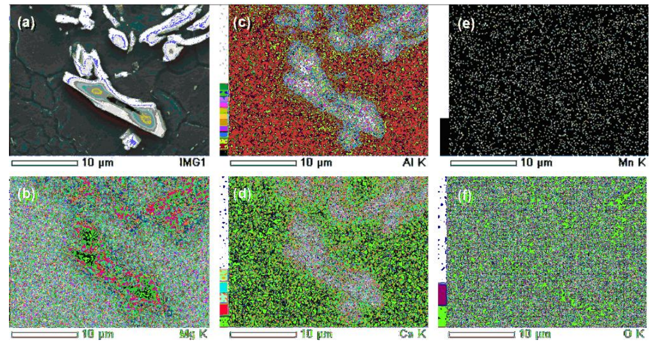

Figure 5 (a)-(f). SEM-EDS of AMX602

The mechanical properties of wrought AMX602 alloys are shown as follows; for example, Fig.6 (a) shows tensile stress-strain curves in extruding the atomized powder compact and cast ingot material at 623 K.

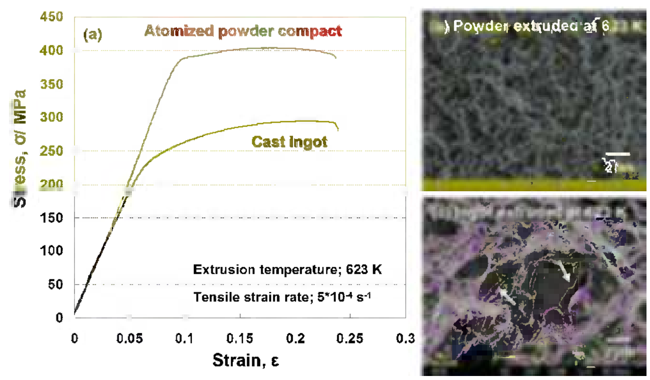

Figure 6(a)-(c). Stress Strain Curve and SEM

The former indicates an increase of TS and YS compared to the ingot extruded alloy of about 35 % and 70 %, respectively. In particular, a phenomenon suspected to yielding is detected when using the powder compact. In the fractured surface of each tensile test specimen, the powder compact extruded alloy 6(b) shows no fracture at primary particle boundaries and fine dimple patterns. This means the particle bonding is strong and cracks propagate inside particles, not grain boundaries. When testing the cast ingot 6(c), dimple patterns are observed, but some cracks occur inside the coarse brittle intermetallics. Figure 7 indicates a dependence of the tensile properties of wrought AMX602 alloys on the extrusion temperature. Both materials reveal the decrease of TS and YS with increase in the extrusion temperature due to their microstructure coarsening. On the other hand, the elongation increases with increasing temperature, and is 14.2 % and 17.7 %, respectively at 623 K. As a noteworthy point, TS of 447 MPa and YS of 425 MPa are obtained in the extruded material by using the rapidly solidified AMX602 powder, which is superior to the conventional aluminum alloy, 2014-T4 heat treatment.

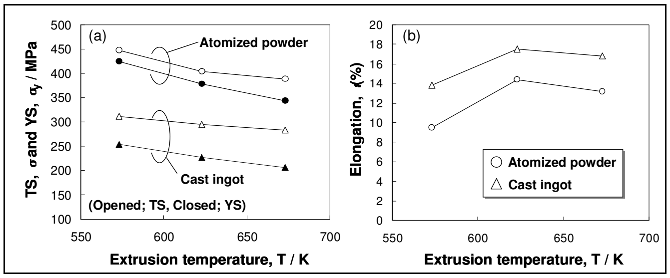

Figure 7. Tensile Properties versus Temperature

The detail characteristics of AZ31B alloy powders and their wrought alloys will be introduced in the conference.

Terminal Ballistic Evaluation

Test Setup

10 magnesium plate samples were produced for ballistic evaluation. The nominal dimensions of the samples were 308-mmx38-mmx5-mm. The test designation and manufacturing of each sample are shown in Table 1. The conventionally rolled plate are designated X--6 and X--7. The thin plates were held vertically in a test fixture by four clamps at the corners of the sample.

TABLE 1. Manufacturing Process

Designation	Material
1--1	AZ31B Swap Cold Compaction Ext 300C
2--1	AZ31B SWAP SPS 200C Ext 300C
4--1	AZ231B Cold Compaction Ext 325C
5--1	AMX 602 Swap Cold Compaction Ext 325C
7--1	AMX 602 Swap SPS 200C Ext 325C
8--1	AZ31B Swap Cold Compaction Ext 350C
9--1	AZ31B SWAP SPS 200C Ext 350C
10--1	AMX 602 Swap SPS 200C Ext 350C
X--6	Mag Coil 1349 Lot 16001 H-24
X--7	Mag Lot 950012 O Temper

Ballistic testing of all magnesium plate samples were performed by the United States Army Research Laboratory (ARL) at Aberdeen Proving Grounds, Maryland in accordance with MIL-STD-662F [6]. Ballistic results were characterized using the standard V_{50} test methodology, also documented in MIL-STD-662F.

Projectile

Because of the thin gauge of the samples, the 0.22-cal fragment simulating projectile (FSP) was selected to evaluate the magnesium alloy plates. The FSP used is produced in accordance with MIL-DTL-46593B (MR) [7] and is depicted in Figure 8. This projectile design is utilized in acceptance tables by current military specifications.

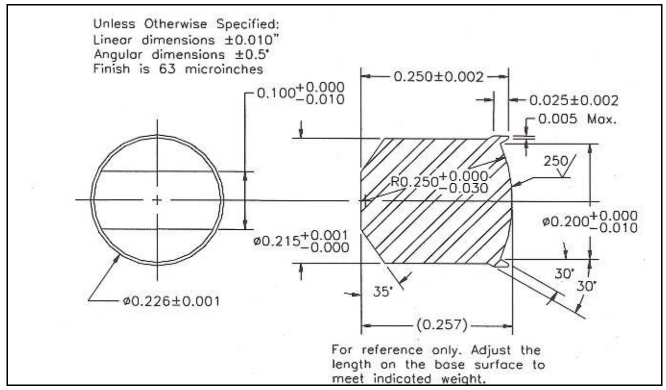

Figure 8. 0.22-cal FSP Dimensions [7]

Ballistic Comparison

Ballistic limits, or V_{50}, of each magnesium plate are shown in Table 2. Each sample was weighed, and the areal density and ballistic limits calculated.

TABLE 2. Areal Weights and Ballistic Limits

Designation	Material	Thickness Inches	Length Inches	Width Inches	Weight Grams	Aeral Density lb/sf	V_{50} m/sec
1--1	AZ31B Swap Cold Compaction Ext 300C	0.192	8.9375	1.5625	77	1.75	277
2--1	AZ31B SWAP SPS 200C Ext 300C	0.191	9	1.5625	78	1.76	269
4--1	AZ231B Cold Compaction Ext 325C	0.193	8.875	1.5625	77.1	1.76	277
5--1	AMX 602 Swap Cold Compaction Ext 325C	0.192	8.9375	1.5625	77.7	1.77	270
7--1	AMX 602 Swap SPS 200C Ext 325C	0.191	8.9375	1.5625	77.1	1.75	268
8--1	AZ31B Swap Cold Compaction Ext 350C	0.192	8.9375	1.5625	77.1	1.75	277
9--1	AZ31B SWAP SPS 200C Ext 350C	0.192	8.9375	1.5625	77.1	1.77	277
10--1	AMX 602 Swap SPS 200C Ext 350C	0.191	8.875	1.5625	77.1	1.76	275
X--6	Mag Coil 1349 Lot 16001 H-24	0.182	8.875	2.5	117.5	1.68	277
X--7	Mag Lot 950012 O Temper	0.187	8.875	2	98.2	1.76	273

The data did not show a statistically significant difference in ballistic performance as a result of processing. The standard deviation of the each V_{50} was within the acceptable required testing limits. Based on this data it is recommended that any future samples have a minimum thickness of 12.7-mm.

Material Response

Initial analysis of the material responses is shown in Table 3 and Figures 9-18. The projectile made an initial indentation, resulting in plastic shearing and the formation of a plug. The back of the samples showed different material failures. AMX602 proved to be a brittle material under all manufacturing processes. Some of the entry holes exhibited cracks due to adiabatic shearing. Large spall failure (scabbing) occurred on the back of the AMX602 samples after the fragment impact. Spalling is the detachment of a layer of material in the area surrounding the location of impact, which may occur on either the front or rear surfaces of a sample. The ductility of this material needs to be improved. The powder manufactured AZ31B petaled during impact which allows some of the energy of the projectile to be dissipated through plastic deformation. Petalling is the peeling of material into segments after impact. Conventionally rolled AZ31B contained the size of the spall failure.

TABLE 3. Material Failure Analysis

Designation	Material	Material Response	
		Front	*Back*
1--1	AZ31B Swap Cold Compaction Ext 300C	Initial indentation, plastic shearing then plug formation	Petalling then spall failure
2--1	AZ31B SWAP SPS 200C Ext 300C	Initial indentation, plastic shearing then plug formation	Petalling then spall failure
4--1	AZ231B Cold Compaction Ext 325C	Initial indentation, plastic shearing then plug formation	Petalling then spall failure
5--1	AMX 602 Swap Cold Compaction Ext 325C	Initial indentation, plastic shearing then plug formation, some shear cracking at hole perimeter	Large spall failure
7--1	AMX 602 Swap SPS 200C Ext 325C	Initial indentation, plastic shearing then plug formation, some shear cracking at hole perimeter	Large spall failure
8--1	AZ31B Swap Cold Compaction Ext 350C	Initial indentation, plastic shearing then plug formation	Petalling then spall failure
9--1	AZ31B SWAP SPS 200C Ext 350C	Initial indentation, plastic shearing then plug formation	Petalling then spall failure
10--1	AMX 602 Swap SPS 200C Ext 350C	Initial indentation, plastic shearing then plug formation, some shear cracking at hole perimeter	Large spall failure
X--6	Mag Coil 1349 Lot 16001 H-24	Initial indentation, plastic shearing then plug formation	Small spall failure
X--7	Mag Lot 950012 O Temper	Initial indentation, plastic shearing	Small spall failure

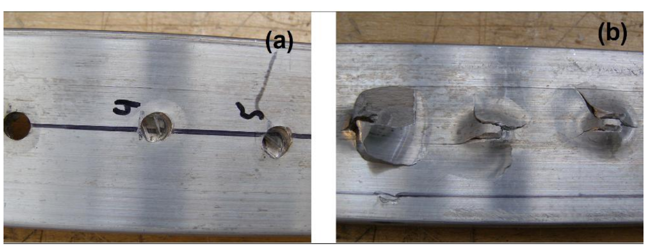

Figure 9. Designation 1--1: Front (a) and Back (b)

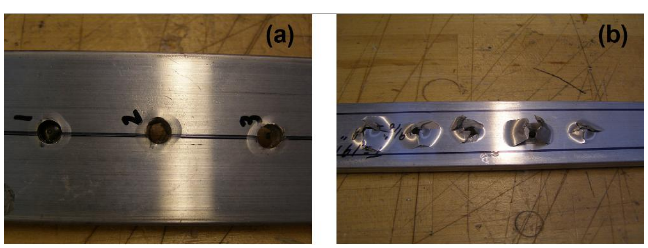

Figure 10. Designation 2--1: Front (a) and Back (b)

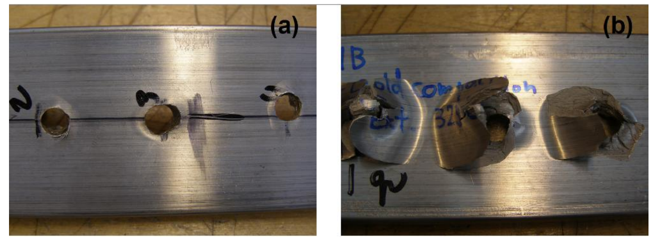

Figure 11. Designation 4—1: Front (a) and Back (b)

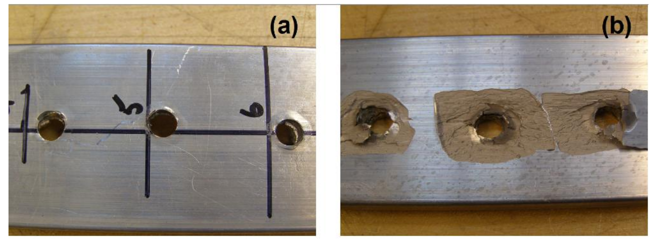

Figure 12. Designation 5--1: Front (a) and Back (b)

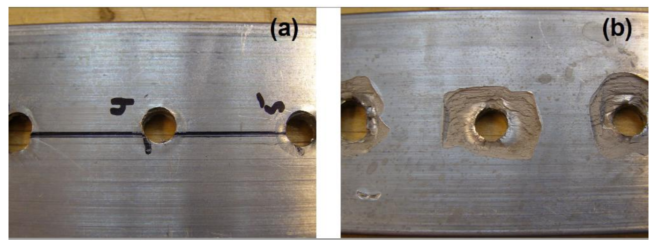

Figure 13. Designation 7--1: Front (a) and Back (b)

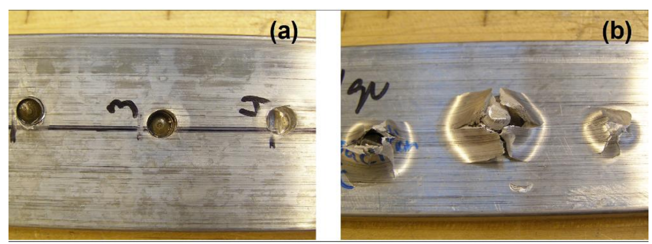

Figure 14. Designation 8--1: Front (a) and Back (b)

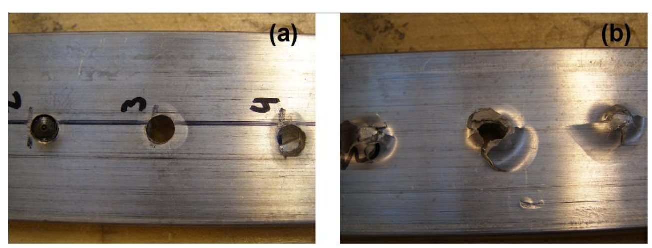

Figure 15. Designation 9--1: Front (a) and Back (b)

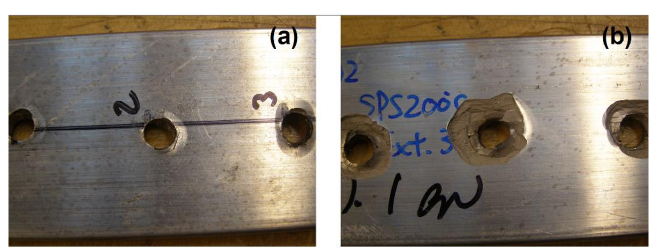

Figure 16. Designation 10--1: Front (a) and Back (b)

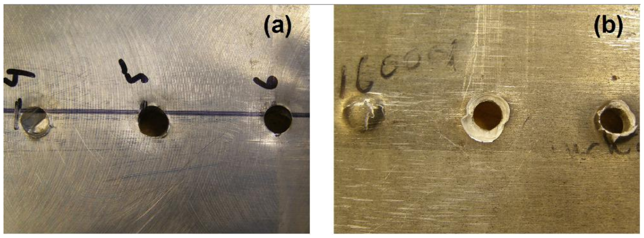

Figure 17. Designation X--6: Front (a) and Back (b)

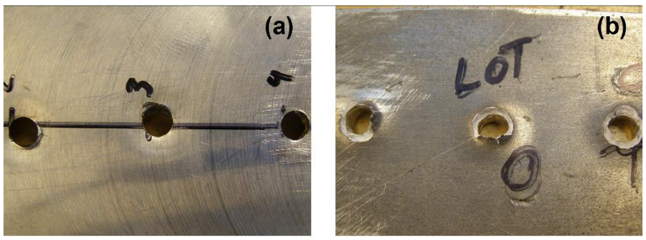

Figure 18. Designation X--7: Front (a) and Back (b)

Conclusion & Future Work

Ballistic performance appears constant regardless of processing route. The magnesium plate may not be thick enough to properly show material differences.

It is recommended that future evaluations be conducted with magnesium plate with a minimum thickness of 12.7-mm.

These results suggest not only high TS and YS, but high elongation caused by sufficient metallurgical bonding between primary powders. Large content of alloy elements in the matrix is not suitable to keep high elongation. The grain and intermetallics refinement is effective to improve the balance of strength and ductility of the magnesium alloys. That is, the thermal history in consolidating rapid solidified magnesium alloy powder should be optimized. The effect of surface oxide (MgO) films of raw powder on the metallurgical bonding is also investigated by microstructural analysis. Furthermore, the materials strengthening by fine dispersoids, which have a good wettability with magnesium, for example, titanium particles will be considered in the future work.

References

[1] Jones, T.L., DeLorme, R.D., Burkins, M.S., & Gooch, W.A.; "A Comparison of the Ballistic Performance between Rolled Plate in AZ31B-H24 Magnesium & 5083-H131 Aluminum"; *Proceedings of the 24th International Symposium on Ballistics*, 2008.

[2] Yoshihito Kawamura, Hideo Mano, Akihisa Inoue: Scripta Materialia, 43, 12 (2000), pp. 1119-1124.

[3] I. Otsuka, H. Izaki: Powder and powder metallurgy, 48, 9 (2001), pp.697-702.

[4] Y. Kitahara, H. Shimazaki: Materials Science Forum Vol.482 (2005), pp.359-362.

[5] Thierry Grosdidier, Gang Ji, Sébastien Launois : Scripta Materialia, 57, 6 (2007), pp.525-528.

[6] Military Standard MIL-STD-662F; "V50 Ballistic Test for Armor", U.S. Army Research Laboratory: Aberdeen Proving Ground, MD, 18 December 1997.

[7] Military Specification MIL-DTL-46593B (MR); "Projectile, Calibers .22, .30, .50, and 20MM Fragment-Simulating", U.S. Army Research Laboratory: Aberdeen Proving Ground, MD, 06 July 2006.