RDECOM

Magnesium Alloys in Army Applications: Past, Current and Future Solutions

Heidi Maupin[1], Eric Nyberg[2] and Suveen N. Mathaudhu[3]

[1] U.S. Army Research Laboratory, Weapons and Materials Research Directorate
[2] Pacific Northwest National Laboratory, Materials Processing
[3] U.S. Army Research Office, Materials Science Division

ARL

TECHNOLOGY DRIVEN. WARFIGHTER FOCUSED.

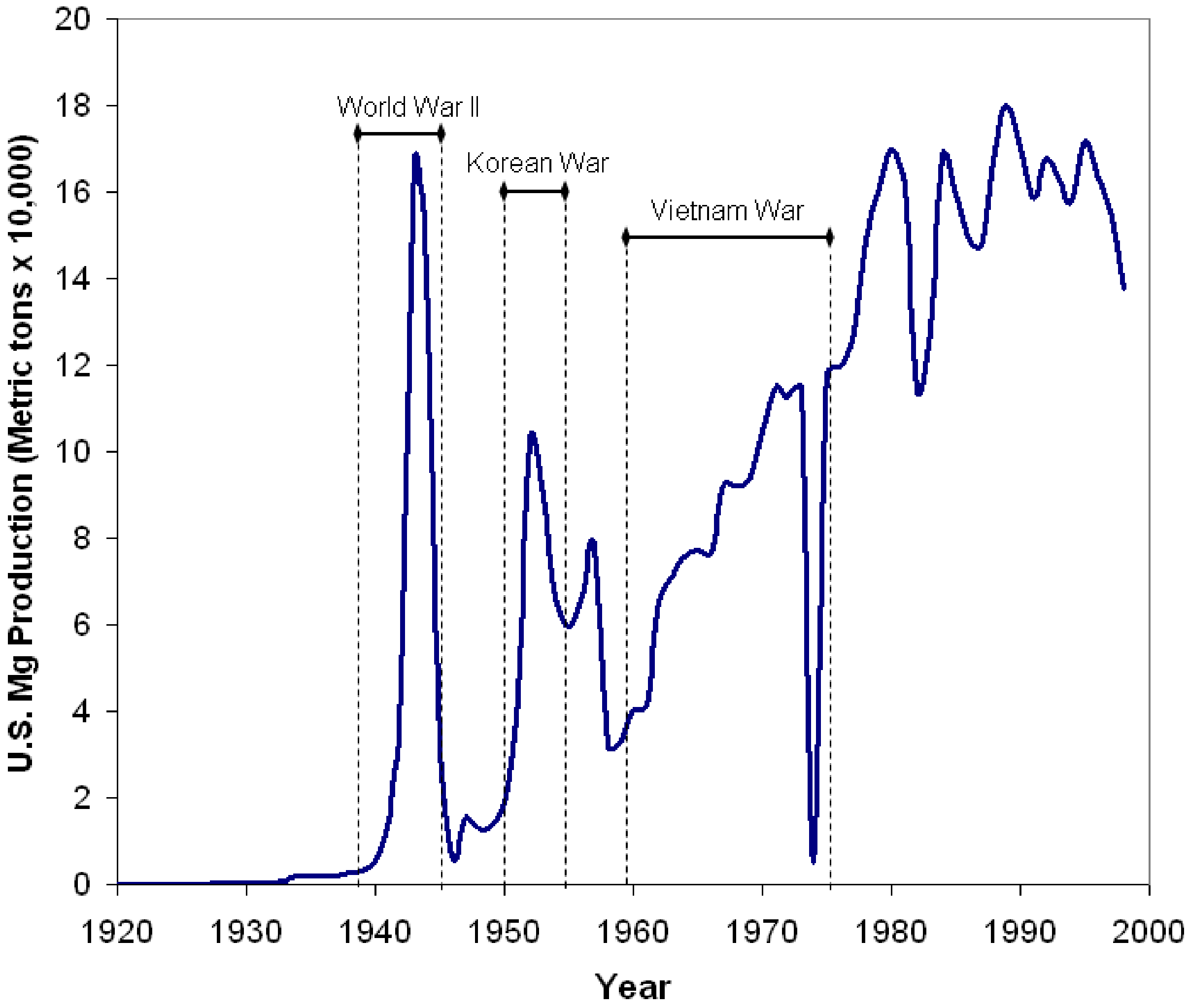
The Sixth Trienniel International Fire & Cabin Safety Research Conference, 25-28 October 2010, Atlantic City, NJ

Session: Magnesium Use in Aircraft

Date: 27 October 2010, 2:00 – 2:30

Unclassified / Cleared For Public Release

U.S. Magnesium Productions by Year



U.S. magnesium metal production by year (1920-1998) showing production spikes during wartime.

(data from the U.S. Geological Survey, Historical Statistics for Mineral and Material Commodities in the United States, Data Series 140, 2007).

World War II Era Applications

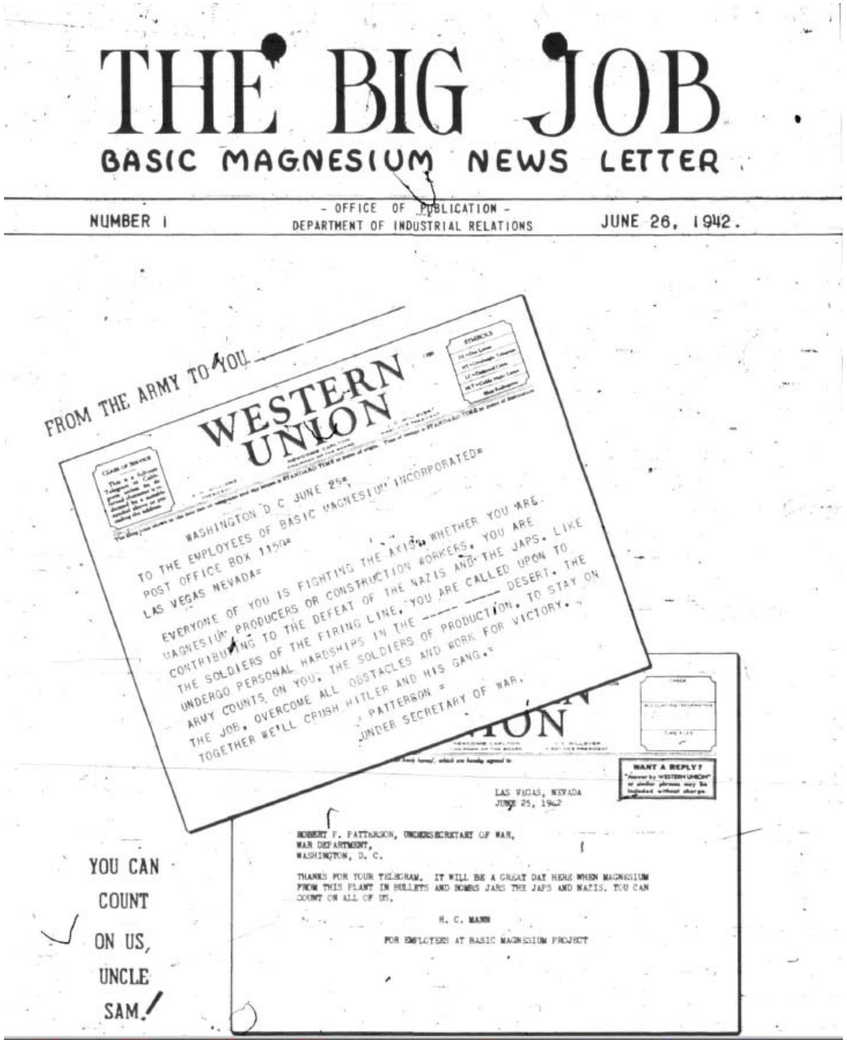
“Straight from the mind of the chemists and engineers has come the formula to win wings from the sea.

Through the efforts of Dow [...] the ocean is yielding its magnesium. For the first time in history man is successfully tapping this inexhaustible benefit of a metal whose phenomenal lightness gives swiftest wings to the airplane so essential to our victory drive.

When victory is ours that extraordinary weight-saving metal - hundreds of millions of pounds annually - will be available for innumerable industrial and domestic purposes.

Magnesium will lighten the tasks of man in countless ways as yet undreamed of, except in the minds of far-seeing engineers and [...] who are already planning the future.” ***- 1942 Dow Chemical Ad***

Magnesium Production was a National Defense Priority



THE BIG JOB

BASIC MAGNESIUM NEWS LETTER

NUMBER 1 — OFFICE OF PUBLICATION — DEPARTMENT OF INDUSTRIAL RELATIONS — JUNE 26, 1942.

FROM THE ARMY TO YOU

WESTERN UNION

WASHINGTON D C JUNE 25=

TO THE EMPLOYEES OF BASIC MAGNESIUM INCORPORATED=
POST OFFICE BOX 1150=
LAS VEGAS NEVADA=

EVERYONE OF YOU IS FIGHTING THE AXIS WHETHER YOU ARE MAGNESIUM PRODUCERS OR CONSTRUCTION WORKERS. YOU ARE CONTRIBUTING TO THE DEFEAT OF THE NAZIS AND THE JAPS. LIKE THE SOLDIERS OF THE FIRING LINE, YOU ARE CALLED UPON TO UNDERGO PERSONAL HARDSHIPS IN THE ----- ----- DESERT. THE ARMY COUNTS ON YOU. THE SOLDIERS OF PRODUCTION, TO STAY ON THE JOB, OVERCOME ALL OBSTACLES AND WORK FOR VICTORY. TOGETHER WE'LL CRUSH HITLER AND HIS GANG.=

PATTERSON =
UNDER SECRETARY OF WAR.

LAS VEGAS, NEVADA
JUNE 25, 1942

ROBERT P. PATTERSON, UNDERSECRETARY OF WAR,
WAR DEPARTMENT,
WASHINGTON, D. C.

THANKS FOR YOUR TELEGRAM. IT WILL BE A GREAT DAY HERE WHEN MAGNESIUM FROM THIS PLANT IN BULLETS AND BOMBS JARS THE JAPS AND NAZIS. YOU CAN COUNT ON ALL OF US.

H. C. MANN

FOR EMPLOYEES AT BASIC MAGNESIUM PROJECT

WANT A REPLY?

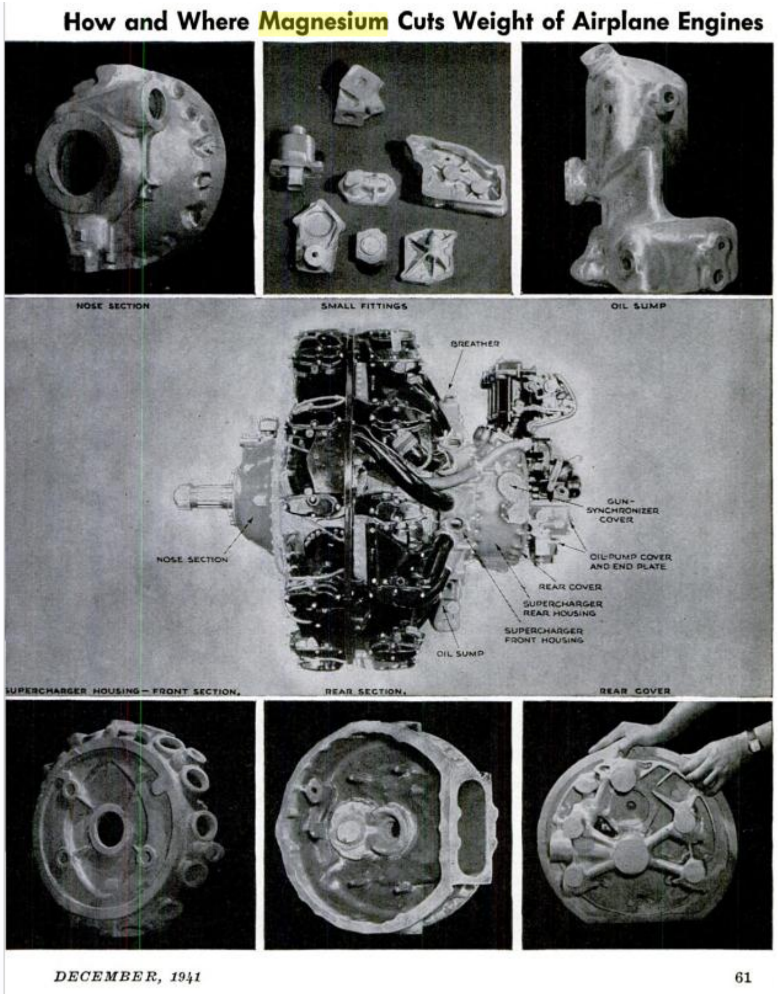
YOU CAN COUNT ON US, UNCLE SAM!

"EVERYONE OF YOU IS FIGHTING THE AXIS WHETHER YOU ARE MAGNESIUM PRODUCERS OR CONSTRUCTION WORKERS. YOU ARE CONTRIBUTING TO THE DEFEAT OF THE [derogatory terms omitted]. LIKE THE SOLDIERS OF THE FIRING LINE, YOU ARE CALLED UPON TO UNDERGO PERSONAL HARDSHIPS IN THE ----- ----- DESERT. THE ARMY COUNTS ON YOU, THE SOLDIERS OF PRODUCTION , TO STAY ON THE JOB, OVERCOME ALL OBSTACLES AND WORK FOR VICTORY. TOGETHER WE'LL CRUSH HITLER AND HIS GANG.

– R. PATTERSON, UNDER SECRETARY OF WAR"

Primary Focus on Aircraft Components (1941)

DURING WORLD W AR II, MAGNESIUM WAS HEAVILY USED IN AIRCRAFT COMPONENTS. IN THIS 1941 PHOTO WORKERS POUR MOLTEN MAGNESIUM INTO A CAST AT THE WRIGHT AERONAUTICAL CORPORATION

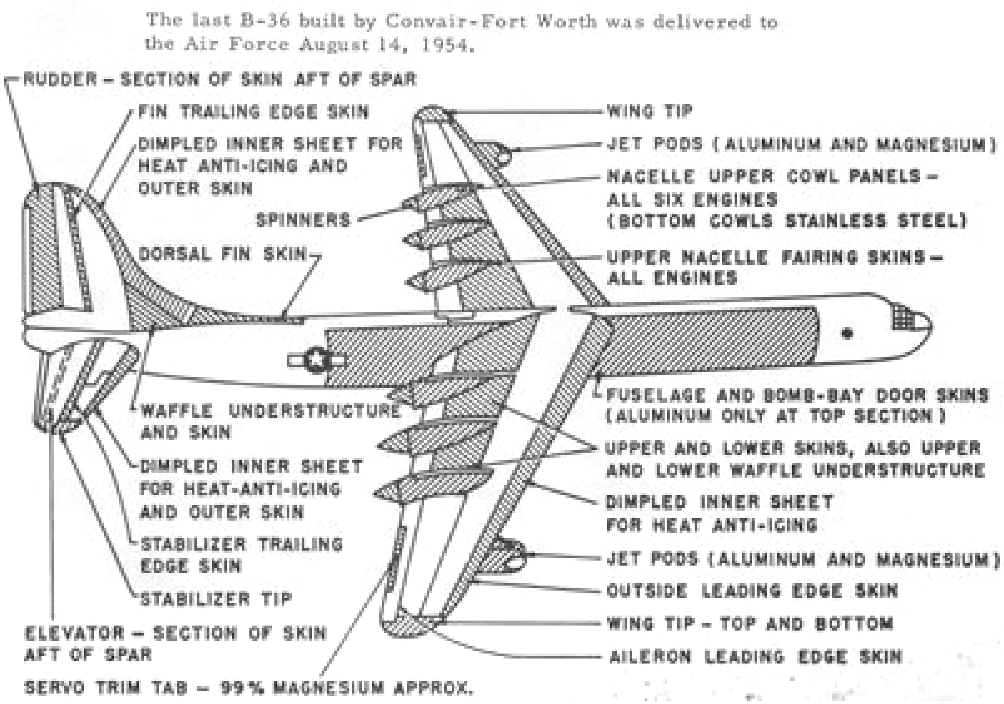


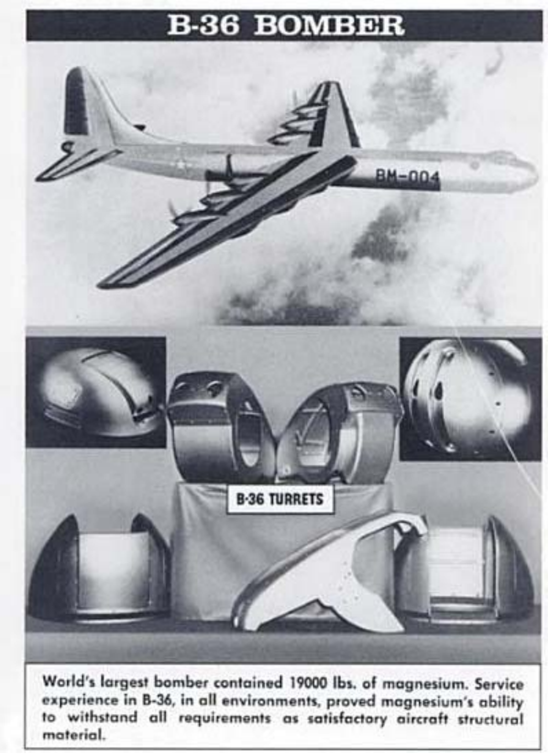
Popular Science, December 1941

B-36 – the "Magnesium Wonder of the World" (1946)

The B-36 incorporated 8,620 kg (19,000 lbs) of Magnesium:

- 5,555 kg (12,200 lbs) of sheet, which covered 25% of the exterior,
- 700 kg (1,500 lbs) of magnesium forgings
- 300 kg (660 lbs) of magnesium castings.



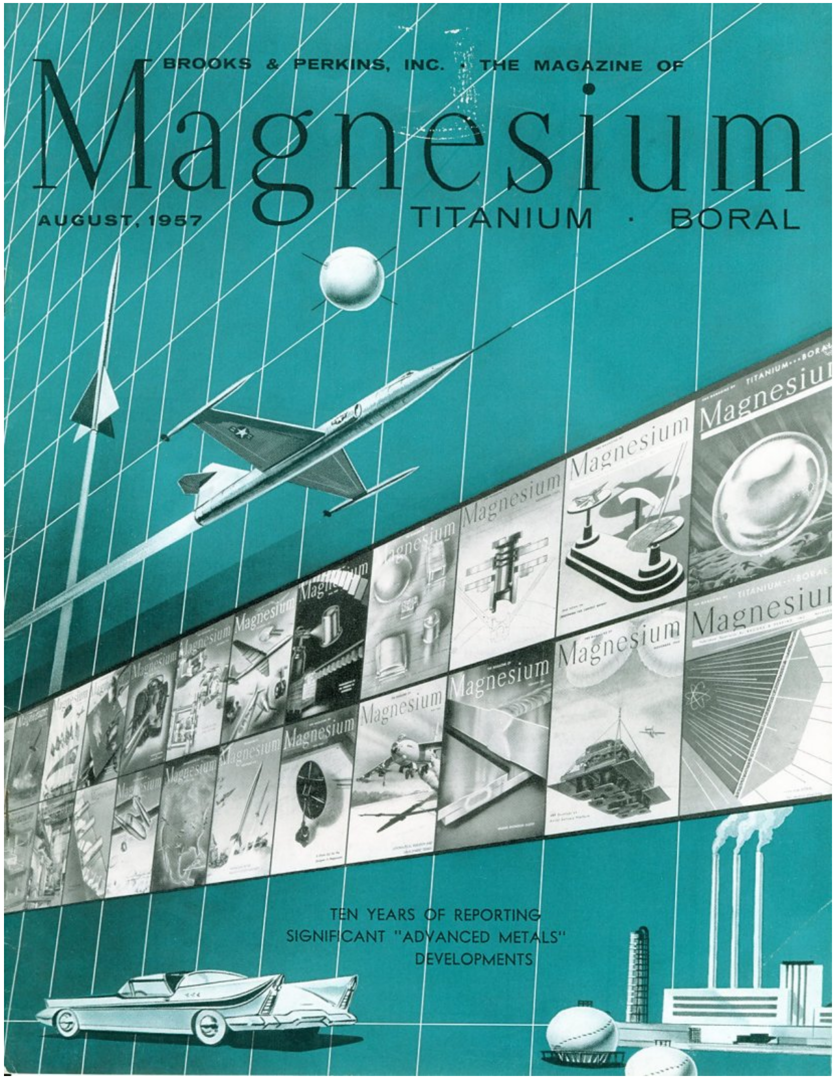


[1-3]

Korean and Vietnam Era Applications

"Ten Years of Reporting Significant "Advanced Metals" Developments"

- August 1957



Sikorsky H-19 “Chicasaw” (1951)

The H-19 Chickasaw holds the distinction of being the US Army's first true transport helicopter and, as such, played an important role in the initial formulation of Army doctrine regarding air mobility and the battlefield employment of troop-carrying helicopters.

The H-19 had the highest percentage (by weight) of magnesium castings and sheet of any aircraft then in service (17%).

[4]

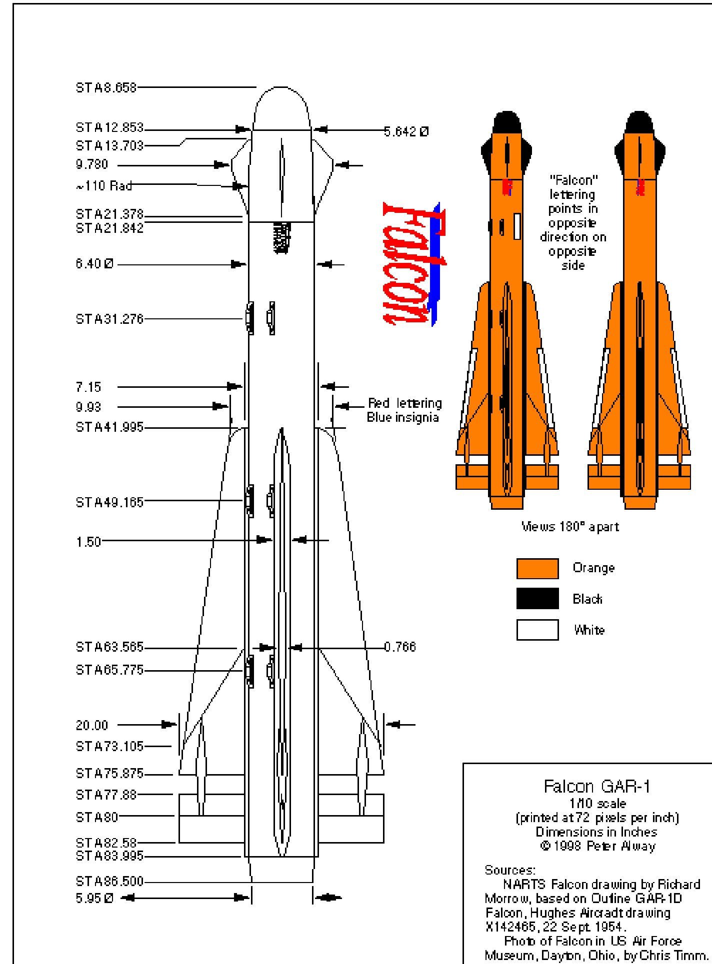
Falcon GAR-1 Missile (1956)

The Falcon GAR-1 was the first air-to-air missile, and had a 90% magnesium structure.

- The stabilizer fins were AZ31B die-casting

- The rudders were ZK60A T5 forgings

- The body was 0.40” thick AZ31B-H24 ` sheet and ZK60A –T5 tubing



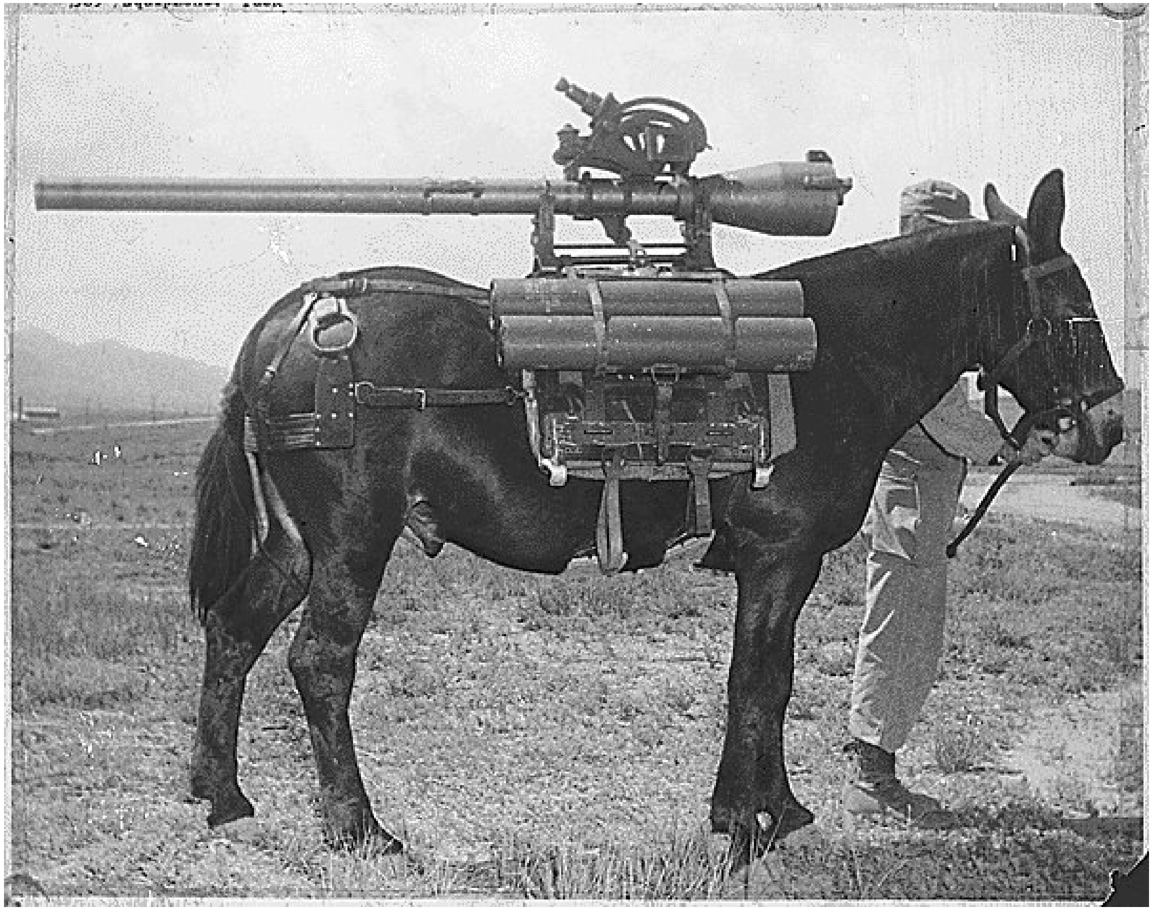
[2]

M-274 Light Cargo, Personnel and Weapons Carrier – "Mule" (1959-1975)

The M274, known as the Mechanical Mule, was developed in the 1950s as a light weight cargo carrier to replace both the 1/4-ton jeep and 3/4-ton trucks in infantry and airborne infantry battalions

The M-274 weighed only 870 lbs, and could transport up to 1000 lbs for 90-150 miles

M-274 Light Cargo, Personnel and Weapons Carrier (1959-1975)



The Army's first attempt to mount a 106 Recoiless Rifle on a mule did not prove successful

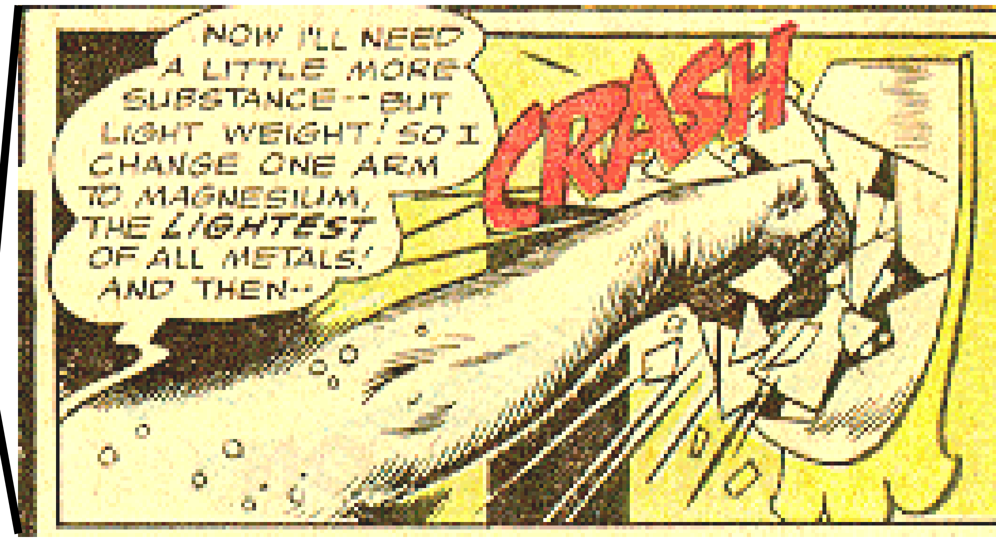
M-274 Light Cargo, Personnel and Weapons Carrier (1959-1975)

Marines of the 106mm platoon, H&S Company, 1st Battalion, 6th Marine Regiment, 2d Marine Division, are seen here preparing to fire on an enemy tank during excerise Express Charger at Camp LeJune, North Carolina.

M-116 Husky Amphibious Personnel Carrier (1957-1973)

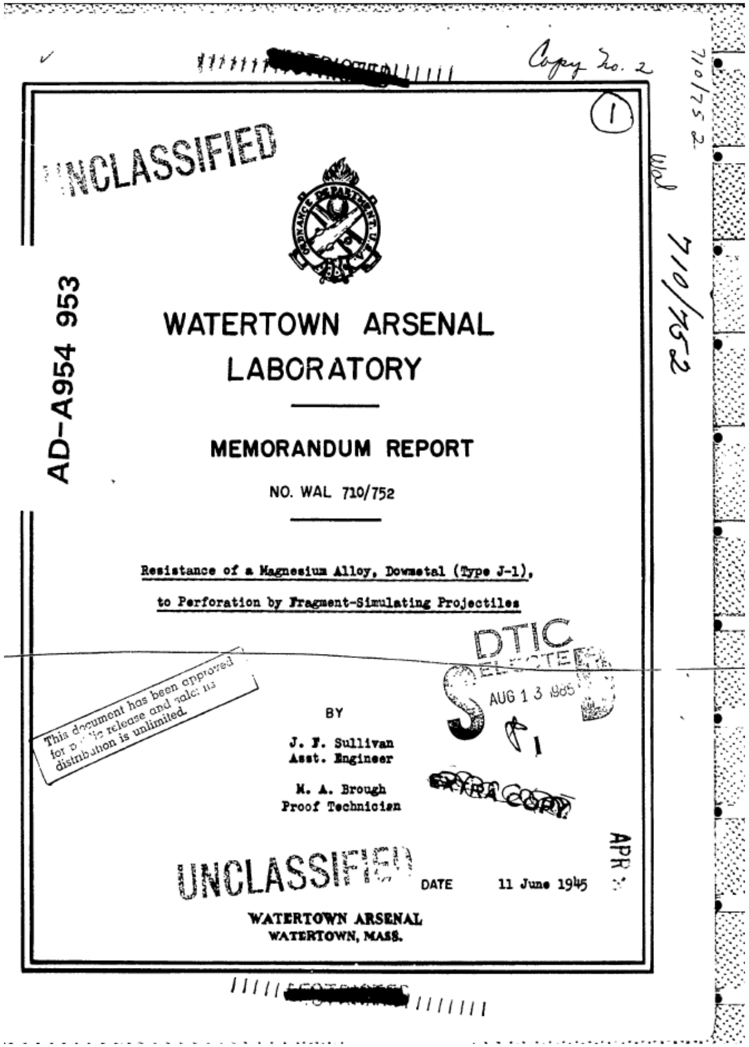
The 60 lb Magnesium floor covered 24.8 ft^2, and was composed of 11.1 in x 1.0 in AZ31B extrusions

The Doom Patrol by DC Comics – (1965)



Mr. 103, the atom master. A renegade scientist, whose experiments in teleportation gave him the power to become any one of the 103 elements known at this time

But what about Armor?


[redacted]

Copy No. 2

UNCLASSIFIED

AD-A954 953

WATERTOWN ARSENAL LABORATORY

MEMORANDUM REPORT

NO. WAL 710/752

Resistance of a Magnesium Alloy, Dowmetal (Type J-1), to Perforation by Fragment-Simulating Projectiles

This document has been approved for public release and sale; its distribution is unlimited.

DTIC ELECTE AUG 13 1985

BY

J. F. Sullivan
Asst. Engineer

M. A. Brough
Proof Technician

EXTRA COPY

UNCLASSIFIED

DATE 11 June 1945

WATERTOWN ARSENAL
WATERTOWN, MASS.

[redacted]

"Dowmetal" (now known as the AM series) was used as an aircraft armor material in the 1940s

These alloys offered better yield strength, hardness and corrosions resistance than prior alloys

But in ballistic testing, perforation resistance was less than face-hardened steel alloys or "Duralumin" (age-hardened aluminum alloys).

Later developments such as Mg-Li alloys improved mechanical properties, corrosion resistance and ballistic response but never took a foothold due to:

- Perceptions of corrosion, poor strength and flammability
- Rapid development of Aluminum alloys
- Increased power capacity in transport systems

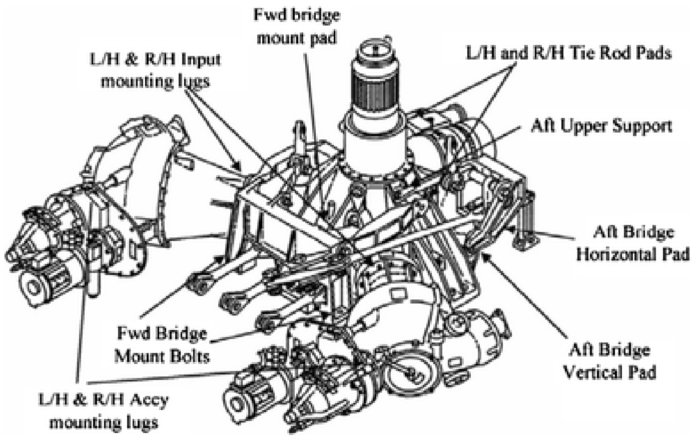
[5-10]

Modern Examples of Magnesium in the Army

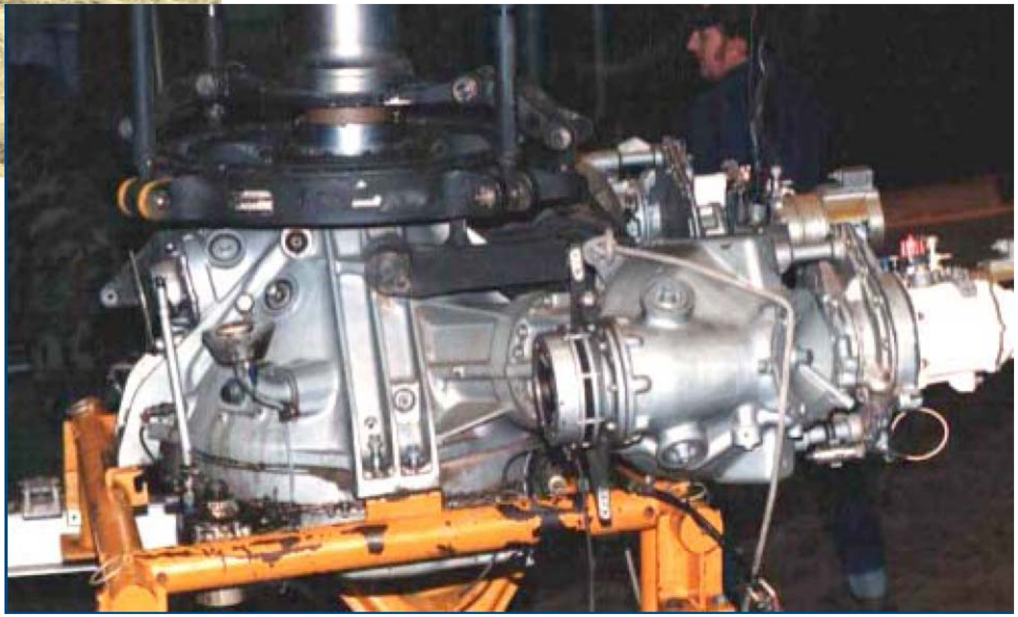
HMMWV "run flat" wheels

[11]

Magnesium is Widely Used for Helicopter Transmission Housings



UH60 Blackhawk Transmission Housing



[12]

Historical Barriers to Military Mg-alloy Usage

Real and Perceived Flammability and Corrosion Problems

Ubiquitous High-School Chemistry Experiment

Garage destroyed at historic manor

"There were several gas containers in there," Lengel said. Also, "the Volkswagen bus they pulled out had an engine that was magnesium" and could have flared up had it made contact with the fire. (©The Mercury, Published: Saturday, February 7, 2009)

Historical Barriers to Military Mg-alloy Usage

Real and Perceived Flammability and Corrosion Problems

Magnesium usage in flares and incendiary munitions has not helped…

Mg must be exposed to temperatures above 600°C for long periods of time, or be in a particulate form with a high surface area to volume ratio to sustainably burn.

[13]

Real and Perceived Flammability and Corrosion Problems

Courtesy of Magnesium Elektron

Sponsored by the U.S. Army Materials Technology Laboratory Center for Excellence for Corrosion and Prevention and Control - (USAMTLCECPC)

Issues:

•Corrosion behavior does not favor high maintainence intervals and long product lifetime

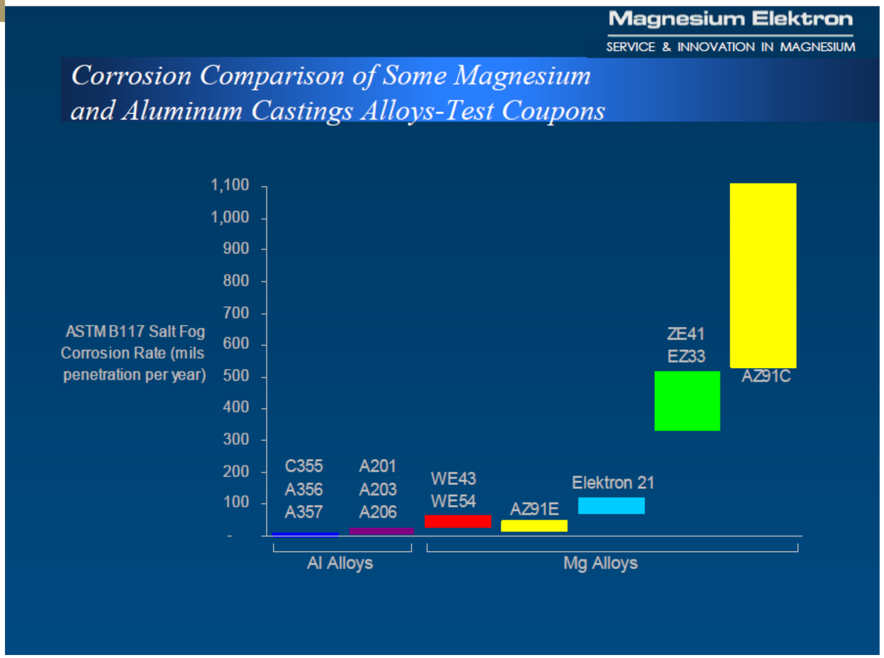
•Wear, abrasion and mechanical damage initiate corrosion even on coated or treated parts

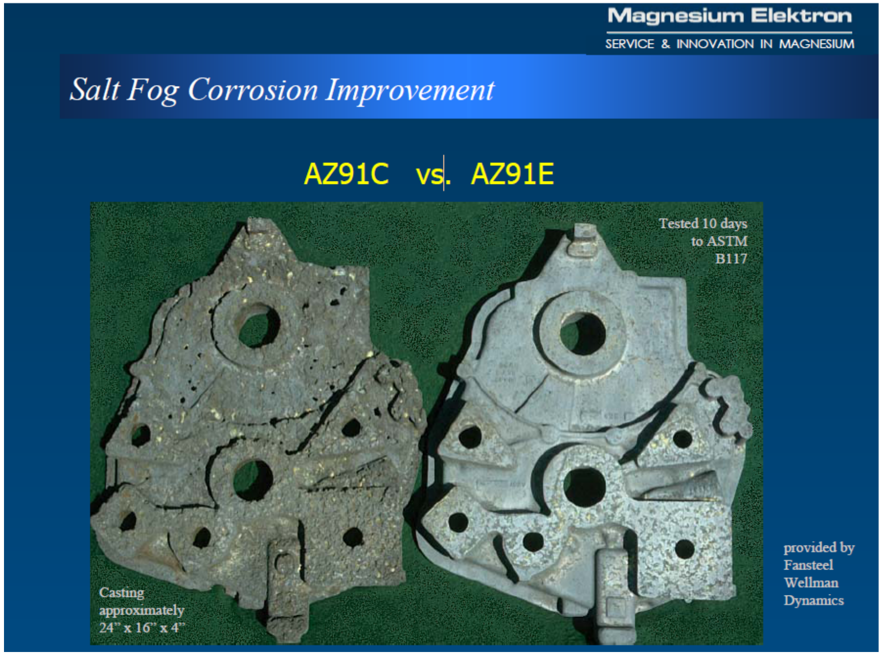
•Poor engineering design involves joining of dissimilar metals and exposure to moisture

Key Roadblock: Difficulty of maintaining corrosion free parts in the field

[14]

Corrosion Inhibition Solutions





High Purity Alloys – limited Fe, Co, Ni and Cu

Coating Solutions Include:

Electrochemical Plating, Conversion Coatings, Anodizing, Gas Phase Deposition, Laser Surface Alloying/Cladding, Organics, Plasma Gel Coating, Cold Spray…

Engineering Solutions Include:

Proper Joint Design, Insulation of Dissimilar Metals, Manufacturing Process Control, Suitable Maintenance Schedules…

[12,15-16]

Strengthening Solutions

Rare-earth Containing Alloys have Markedly Improved the Mechanical Properties of Mg-Alloys while Improving Corrosion and Flammability Resistance

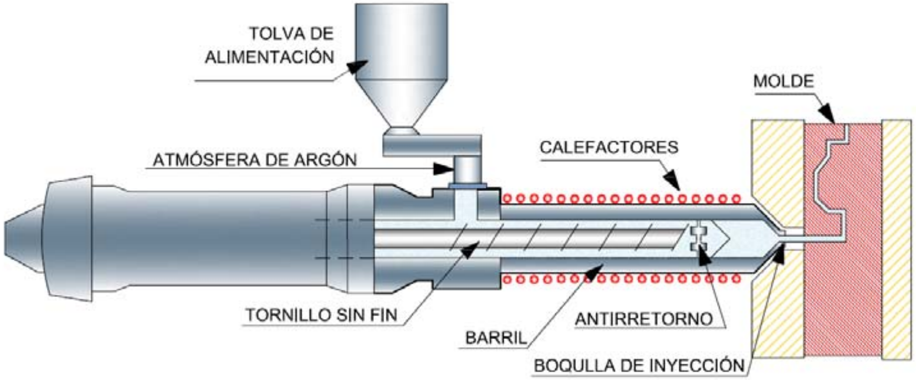
Alloy Designation	Tensile Strength (MPa)	0.2% Proof Stress (MPa)	Elong. to Failure (%)	Magnesium Elektron Datasheet*
AZ31B-H24	235	125	7	482
ZK60A-T5	290	180	6	486
AZ91E-T6	270	170	4.5	456
Electron 21	280	170	5	455
WE54-T5	300	200	10	480
WE43-T5	280	195	10	478
Elektron 675	410	310	9	102

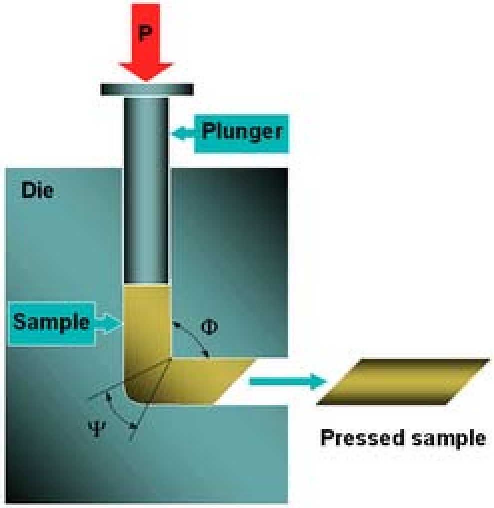
* http://www.magnesium-elektron.com/.

Other Strengthening Solutions

- Thixomolding
- Rapid Solidification
- Twin-Roll Casting
- Severe Plastic Deformation
- Many more…

scienceimage.csiro.au © CSIRO



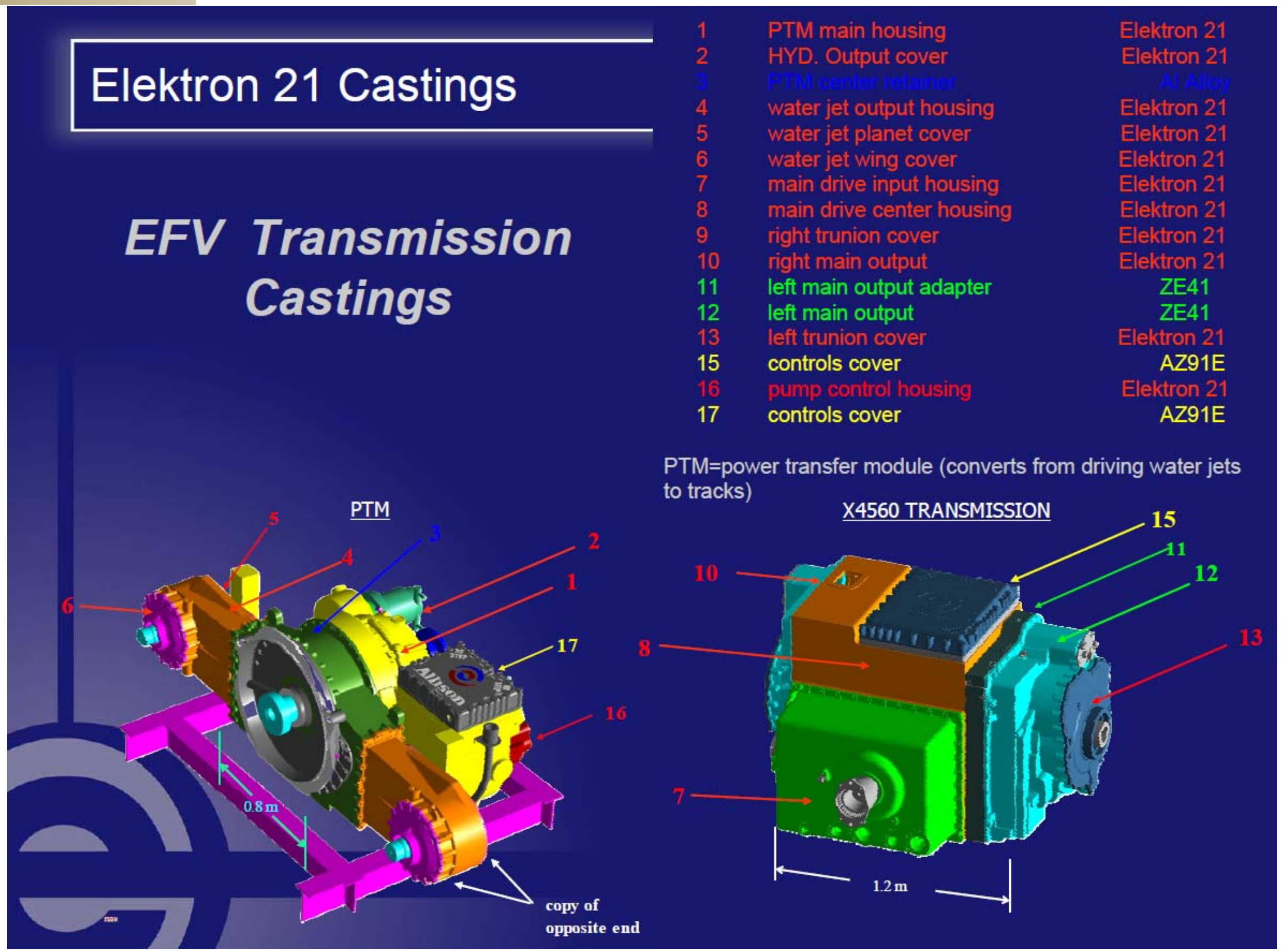


[17-21]

Improved Properties Give Mg-Alloys New Opportunities

"Magnesium in Aerospace Applications: Past Concerns, Current Solutions" Bruce Gwynne and Paul Lyon - Magnesium Elektron, Triennial International Aircraft Fire & Cabin Safety Research Conference, October 29 – November 1, 2007 [13]

Improved Properties Give Mg-Alloys New Opportunities



"Magnesium in Aerospace Applications: Past Concerns, Current Solutions" Bruce Gwynne and Paul Lyon - Magnesium Elektron, Triennial International Aircraft Fire & Cabin Safety Research Conference, October 29 – November 1, 2007 [13]

Magnesium Armor Redux

Based on Tremendous Property Improvement, there is Renewed Interest in Mg-Alloys for Vehicle and Personnel Armor Protection

target

AZ31B-H24 Mg-alloy shows better ballistic performance than 5083-H131 Al-alloy against the armor-piercing projectiles on a per-weight basis

- T. Jones and R. D. DeLorme, "Development of a Ballistic Specification for Magnesium Alloy AZ31B"
- T.L. Jones, R.D. DeLorme, M. S. Burkins and W.A. Gooch, "Ballistic Evaluation of Magnesium AZ31B" T. Jones and K. Kondoh, "Initial Evaluation of Advanced Powder Metallurgy Magnesium Alloys for Armor Development"
- F.T.M. van Wegen and E.P. Carton, "New Lightweight Metals for Armors"

[22-25]

New Magnesium Military Specification (2009)

- MIL-DTL-32333 (Armor Plate, Magnesium Alloy, AZ31B, Applique) is the first US magnesium armor plate military specification.
- MIL-DTL-32333 will provide troops with a lighter weight solution for ultimate protection in the field, as well as improved mobility and fuel efficiency for military hardware
- MIL-DTL-32333 will encourage materials engineers to think out-of-the-box during the design phase.
- WE43 and new Elektron 675 alloy are also under development in rolled sheet and plate form, with the intention of incorporating these alloys within the new armor plate spec when the ballistic testing is complete, and in conjunction with the USARL

[26]

Magnesium for Personnel Protection

Prototype Mg-Alloy Helmet Shell (S. Walsh – ARL)

[27]

Questions Which Will Need Answers…

1. Where is magnesium suitable for military hardware?
2. What is holding back the use of magnesium?
3. What can be done to overcome objections to the use of magnesium?
4. What are the prospects for success in such activities?
5. How much time will be required to establish the basis for greater use of magnesium?

The Far Future: Barrier Scientific Issues

INTRINSIC SCIENTIFIC ISSUES

-Poor Strength, Formability and Ductility: HCP Crystal Structure and Anisotropy

-Poor Temperature Stability/Fatigue/Creep Resistance: Low T_m System

-Poor Corrosion Resistance: Poor Inherent Properties and Galvanic Coupling

EXTRINSIC SCIENTIFIC ISSUES

-Perceived Flammability: High School Chemistry Experiment

-Alloy and Composite Development: Low Economic Drive

-Unknown Fundamental Deformation Mechanisms: Limited Characterization Tools

-High Strain Rate Behavior not Well Known

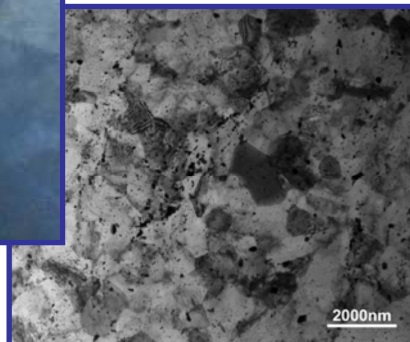
-Lag in Computational Materials Engineering and Design

Properties can be Tailored by Structural Manipulation on Multiple Length Scales

1 m

Application

Lightweight Armor



1 – 100 mm

Macrostructure

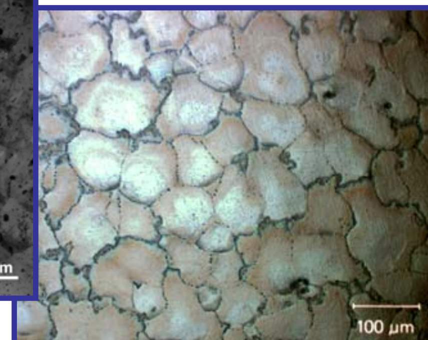
Grains

Macroporosity

Properties

High Cycle Fatigue

Ductility



10 – 500 μm

Microstructure

Second Phases

Dendrites

Microporosity

Intermetallics

Properties

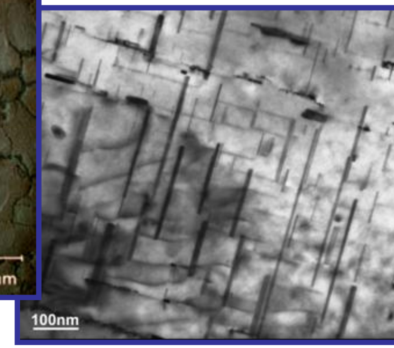
Yield Strength

Tensile Strength

Low Cycle Fatigue

Ductility

Thermal Growth



1 – 100 nm

Nanostructure

Sub-grains

Precipitates

Defects

Properties

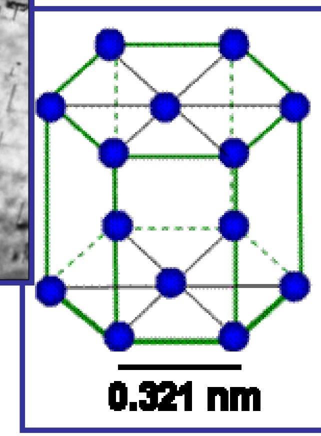
Yield Strength

Tensile Strength

Low Cycle Fatigue

Ductility

Thermal Growth



0.1 – 1 nm

Atomic Scale

Crystal Structure

Interfaces

Properties

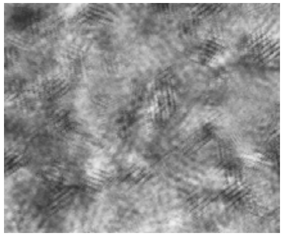
Yield Strength

Thermal Growth

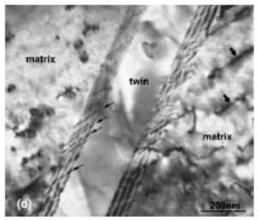
[28]

Multiscale Computational Materials Design of Mg Alloys and Systems

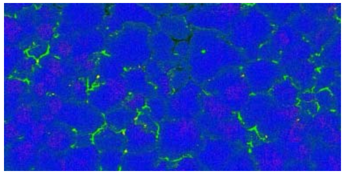
Experiments



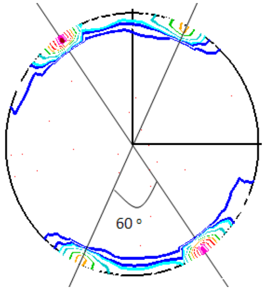
HRTEM [1]



Metallography

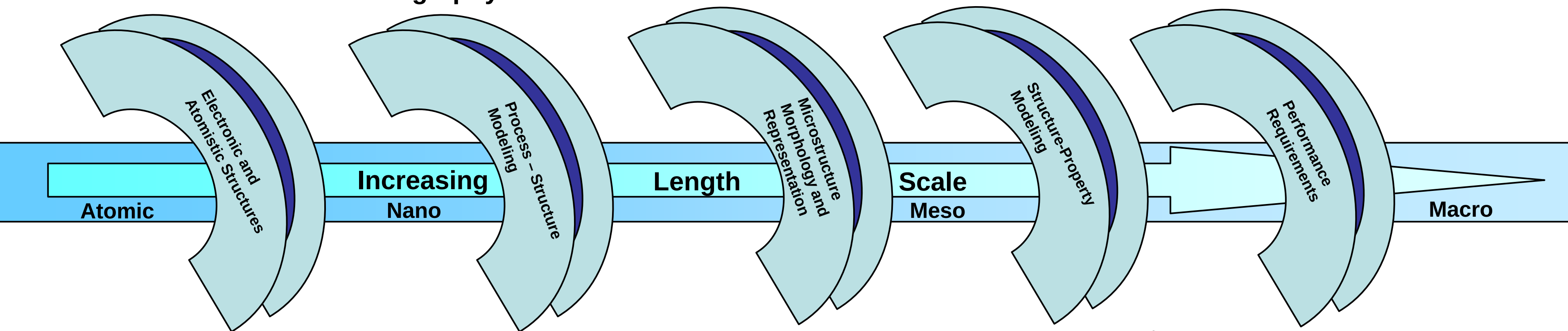


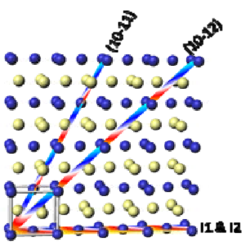
Electron Microprobe



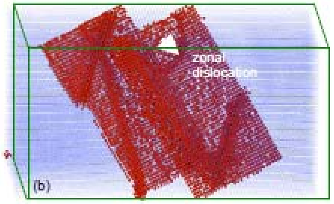
X-Ray Texture Measurement

Deformation Processing

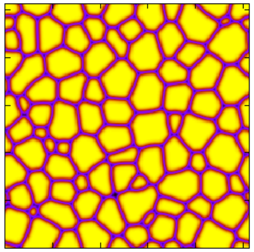




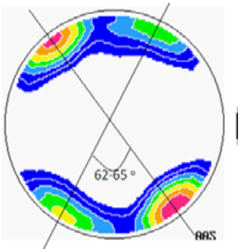
First Principles Simulations



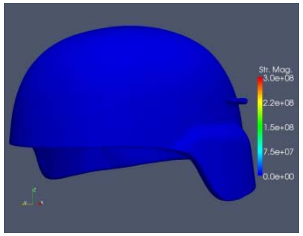
Molecular Dynamics Simulations



Phase Field Simulations



Crystal Plasticity Modeling



Finite Element Methods

[29-30]

Simulations

[1] "HRTEM observation of the metastable phases in Mg-Gd-Y-Zr alloy" Y. Fukuda,T. Kawabata, K. Matsuda, S. Kamado,Y. Kojima, S. Ikeno, Microsc Microanal 11(Suppl 2), 2005

Summary

Past

Commonly used in aircraft and vehicle structural platforms, and lethality applications. Not used at all for personnel protection or armor applications.

Present

Most commonly used in vehicle and helicopter transmission housing. No current lethality or armor applications, but systems are being developed which may change this

Future

A vision must be developed for creating new ground and air vehicle structural applications in addition to new personnel protection and armor applications. To accomplish this, modern day tools must be used to address the significant scientific challenges which have prevented prior usage.

One Last Quote…

*“The market for magnesium may be expected to develop along lines similar to those along which aluminum developed, but whether to anything like the same extent is entirely problematic. The market is somewhat unacquainted with many of the special qualities of the metal, and increased sales are largely a matter of education and research whereby a demand will be created and developed hand in hand with production. […] The importance of a metal with properties similar to that of aluminum, but nearly half as light in these days of enormous automobile and aircraft expansion hardly needs much argument.” - **1919** United States Bureau of Mines Bulletin*

[31]

Questions?

?

- ***Contact Information:***

Ms. Heidi Maupin - Chief
Lightweight and Specialty Metals Branch
Attn: RDRL-WMM-F
Aberdeen Proving Ground, MD 21005
Work: 410.306.0636
Fax: 410.306.0759
E-mail: heidi.maupin@us.army.mil

Acknowledgements

- Jonathan Montgomery, James McCauley, Robert Dowding, Kyu Cho, Shawn Walsh, Tyrone Jones and Ernest S.C. Chin of the U.S. Army Research Laboratory
- Robert E. Brown of Magnesium Assistance Group, Inc.
- Scott Shook of Applied Magnesium - International Group
- Bruce Davis and Rick DeLorme of Magnesium Elektron
- Neale Neelameggham of U.S. Magnesium

References

1. B.B. Clow, "Magnesium: The Lightest One," *Metallic Materials for Lightweight Applications: Proceedings of the 40th Sagamore Army Materials Research Conference*, eds. Martin G.H. Wells, Eric B. Kula and John H. Beatty (Washington, D.C., Government Printing Office, 1993), 235-239.
2. H.E. Friedrich and B.L. Mordike, eds., *Magnesium Technology: Metallurgy, Design Data, Applications* (New York, NY: Springer, 2006), 610-620.
3. I.J. Polmear, "Magnesium and Magnesium Alloys" *ASM Specialty Handbook*, eds. M.M. Avedesian and H. Baker (Materials Park, OH: ASM International, 1999), 5.
4. L.S. Tagg, "On the Front Line of R&D: Wright Patterson Air Force Base in the Korean War, 1950-1953" Aeronautical Systems Center History Office. 2001. Wright Patterson Air Force Base. 9 September 2009, http://www.ascho.wpafb.af.mil/korea/contents.htm
5. J.F. Pashak, "Production and Fabrication of LA142 Pellets" (Report Department of the Army/AD409845, Dow Metal Products Company, 1963).
6. T.G. Byrer, E.L. White and P.D. Frost, "The Development of Magnesium-Lithum Alloys for Structural Applications" (Report NASA/NAS8-5049, Battelle Memorial Institute, 1964).
7. J.F. Sullivan and M.A. Brough, "Resistance of a Magnesium Alloy, Dowmetal (Type J-1), to Perforation by Fragment-Simulating Projectiles" (Memorandum Report/AD-A954953, Watertown Arsenal Laboratory, 1945).
8. J.F. Sullivan, "Aircraft Armor - Perforation Resistance Characteristics of Magnesium Alloys, (Dowmetal Type FS, J-1)" (Experimental Report/AD-A954259, Watertown Arsenal Laboratory, 1944).
9. J.F. Sullivan, "Aircraft Armor - Ballistic Characteristics of a Magnesium Alloy (Type FS)" (Memorandum Report/AD-A954458, Watertown Arsenal Laboratory, 1943).
10. S. Isserow, "Investigation of Microquenched Magnesium ZK60A Alloy" (Final Report/AMMRC TR 74-1, Army Materials and Mechanics Research Center, 1974).
11. M. Green and G. Steward, Humvees at War (St. Paul, MN: Zenith Press, 2005), 39.
12. V.K. Champagne, "The Repair of Magnesium Rotorcraft Components by Cold Spray," Journal of Failure Analysis and Prevention, 8 (2008), 164-175.
13. N. Jeal, "High-Performance Magnesium," Advanced Materials & Processes, 9 (2005), 65-67.
14. S. Isserow and R.S. Busk, "Workshop on the Viability of Magnesium in Military Hardware" (Special Publication/MTL-SP-87-7, U.S. Army Materials Technology Laboratory, 1987).
15. I. Ostrovsky and Y. Henn, "Present State and Future of Magnesium Application in Aerospace Industry" (Paper presented at ASTEC'07 International Conference– New Challenges in Aeronautics, Moscow, Russia, 19-22 August 2007), 1-5.

References

16. J.E. Gray and B. Luan, "Protective Coatings on Magnesium and its Alloys – a Critical Review," *Journal of Alloys and Compounds*, 336 (2002), 88-113.
17. J. Mihelich and R.F. Decker, US Patent No 5.711.366, 1998 and US Patent No 5.819.839, 1998.
18. H. Watari, T. Haga, N. Koga, and K. Davey, "Feasibility Study of Twin Roll Casting Process for Magnesium Alloys,"*Journal of Materials Processing Technology*, 192-193 (2007), 300-305.
19. C.A. Lavender, M.T. Smith and M.R. Garnich, "Development of Rapidly Solidfied Magnesium Alloys" (Contractor Report / BRL-CR-682, Ballistic Research Laboratory, 1992).
20. S.R. Agnew, P. Mehrotra, T.M. Lillo, G.M. Stoica, and P.K. Liaw, "Texture Evolution of Five Wrought Magnesium Alloys during Route A Equal Channel Angular Extrusion: Experiments and Simulations," *Acta Materialia*, 53 (2005), 3136-3146.
21. S.X. Ding, W.T. Lee, C.P. Chang, L.W. Chang, P.W. Kao, "Improvement of Strength of Magnesium Alloy Processed by Equal Channel Angular Extrusion", Scripta Materialia, 59 (2008) 1006-1009.
22. T. Jones and R. D. DeLorme, "Development of a Ballistic Specification for Magnesium Alloy AZ31B" (Technical Report / ARL-TR-4664, Army Research Laboratory, 2008).
23. T.L. Jones, R.D. DeLorme, M. S. Burkins and W.A. Gooch, "Ballistic Evaluation of Magnesium AZ31B" (Technical Report / ARL-TR-4077, Army Research Laboratory, 2007).
24. T. Jones and K. Kondoh, "Initial Evaluation of Advanced Powder Metallurgy Magnesium Alloys for Armor Development" (Technical Report / ARL-TR-4828, Army Research Laboratory, 2009).
25. F.T.M. van Wegen and E.P. Carton, "New Lightweight Metals for Armors" Proceedings of the 24th International Symposium on Ballistics, ed. S. Bless and J. Walker, CD Proceedings, 2008, 1-9.
26. K. Cho, T. Sano, K. Doherty, C. Yen, G. Gazonas, J. Montgomery, P. Moy, B. Davis and R. DeLorme, "Magnesium Technology and Manufacturing for Ultra Lightweight Armored Ground Vehicles" (Reprint from 2008 Proceedings of the 2008 Army Science Conference / ARL-RP-236, Army Research Laboratory, 2009).
27. S.M. Walsh, B.R. Scott, T.L. Jones, K. Cho and J. Wolbert, " A Materials Approach in the Development of Multi-Threat Warfighter Head Protection," Proceedings of the 2008 Army Science Conference, Orlando, FL, December 2008, 8.
28. E. Ma, K.T. Ramesh, R. Dowding and J.W. McCauley, "International Magnesium Workshop" (Scientific Report / ARL-SR-162, Army Research Laboratory, 2008).
29. H. Zhang, Y. Wang, S. Shang, L.Q. Chen and Z.K. Liu, "Thermodynamic Modeling of Mg-Ca-Ce System by Combining First-Principles and CALPHAD Method," Journal of Alloys and Compounds, 263 (2008) 294-301.
30. T. Uesugi and K. Higashi, "Materials Design for High-Strength Mg-based Alloys by Understanding from Ab-Initio Calculation," Materials Science Forum, 488-489 (2005), 131-134.
31. "Make Our Own Magnesium", the New York Times, 4 July 1920.