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3 PROPERTIES AND CURRENT APPLICATIONS OF MAGNESIUM-LITHIUM ALLOYS

A REPORT

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3 PROPERTIES AND CURRENT APPLICATIONS OF MAGNESIUM-LITHIUM ALLOYS 6

A REPORT

By

(R.J. Jackson and P.D. Frost 7

Prepared under contract for NASA

by Battelle Memorial Institute

Technology Utilization Division

OFFICE OF TECHNOLOGY UTILIZATION 9 1967 10CY

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

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Foreword

The Administrator of the National Aeronautics and Space Administration has established a Technology Utilization Program for the rapid dissemination of information on technological developments that appear to be useful for industrial application. From a variety of sources, such as NASA research centers and NASA contractors, space-related technology is screened, and that which has potential industrial use is made generally available.

This publication is one of a series designed to provide such technological information.

This is the second special report on the magnesium-lithium alloys. The first study, entitled "Technical and Economic Status of Magnesium-Lithium Alloys" (August 1965) was a report to management on general characteristics of the alloys, current applications, and economic considerations for their future use. The first report did not include detailed engineering information.

This second report provides such information. In addition to mechanical and physical data, it contains information on melting, casting, fabricating, joining, and finishing magnesium-lithium alloys. Applications, producers, and specifications are also described.

GEORGE J. HOWICK, *Director,*
Technology Utilization Division,
National Aeronautics and Space Administration.

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CHAPTER 1

Applications

AEROSPACE USES

Magnesium-lithium alloys are the lightest metals currently available for aerospace applications. The commercial alloy LA141A (nominal composition: Mg-14Li-1Al) is approximately 25 percent lighter than conventional magnesium alloys and is 27 percent lighter than beryllium. As light as most plastics, it has the stiffness of a metal. This combination of lightness and stiffness has established LA141A as one of the most interesting aerospace metallic materials. Industrial interest in LA141A for missiles and space vehicles has come about only in the last 4 years (ref. 1), although serious development of magnesium-lithium alloys started in this country as early as 1944. Like many other technical developments, the magnesium-lithium alloys were developed for a purpose that did not materialize, and existed for a number of years before they were "discovered" for lightweight aerospace use.

NASA was largely responsible for the introduction of magnesium-lithium alloys to the manufacture of missiles and space hardware through sponsorship by one of its predecessors, the Army Ballistic Missile Agency (ABMA), of the first research to evaluate these alloys for possible missile and space use. The report (ref. 2), which received wide distribution, presented mechanical properties, corrosion resistance, weldability, and physical properties of the alloys. Since 1960, aerospace companies, notably the Lockheed Missiles and Space Co. (LMSC) and the Federal Systems Division of International Business Machines Corp. (IBM), have made good use of the information presented in the NASA report, and have generated much more data on the properties and uses of the LA141A alloy.

In addition to the LA141A alloy, several other magnesium-lithium alloys recently have been developed and designated. One of the new alloys, designated LAZ933A, was developed under NASA sponsorship at Battelle (ref. 3) and currently is being evaluated by NASA for tankage and structural applications in advanced spacecraft designs. The LAZ933A alloy has been successfully produced as foil and fabricated into honeycomb structure (ref. 4). Two other new alloys, designated Mg–14Li–0.5Si and Mg–14Li–5Zn–3Ag–2Si, are casting compositions developed by Frankford Arsenal (refs. 5, 6, and 7). These alloys are also currently being evaluated for applications in aerospace components. Some typical components (ref. 8) made of LA141A alloy are:

(1) Gemini guidance computer
  (a) Cross-over detector support
  (b) Circuit module cans

(2) Saturn V launch-vehicle data adaptor
  (a) Main distribution panel
  (b) Housing structure
  (c) Cover and back panels
  (d) Chassis

(3) Saturn V launch-vehicle digital computer
  (a) memory plate
  (b) frame
  (c) sealed cover.

In the fabrication of these components, extensive know-how in machining, fabricating, welding, and coating was developed.

In addition to use in the Agena booster and in a number of payloads put in orbit by the Agena, the following types of applications have proven successful (ref. 9):

(1) Electronic packaging
  (a) Fabricated boxes and covers for non-pressurized components
  (b) Deep-drawn boxes

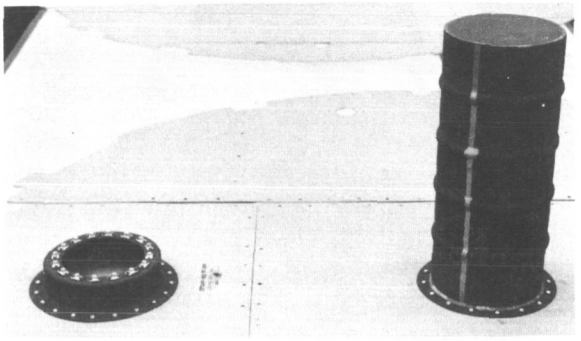

FIGURE 1.—The cylindrical structure is an 0.040-inch thick sheet of LA141A, rolled, welded, and beaded. It is pressurized for flight. The small unit was spun.

(2) Mounted segments: angles, channels, sections, and Z-sections
(3) Mounted clips for microwave guides
(4) Spun air-conditioning duct work
(5) Pressure and dust panels
(6) Antenna-mounted structures
(7) Gyro mounts
(8) Brackets for electronic connections
(9) Heat shields.

Many of these parts have been used in successful space missions as may be seen in figures 1 through 4.

In addition, the alloys have been considered for use in the Minuteman and the Manned Orbiting Laboratory. To date, all applications for magnesium-lithium alloys have been in secondary or nonstructural designs (ref. 10).

For a more comprehensive summary of magnesium-lithium alloy development, see appendix A.

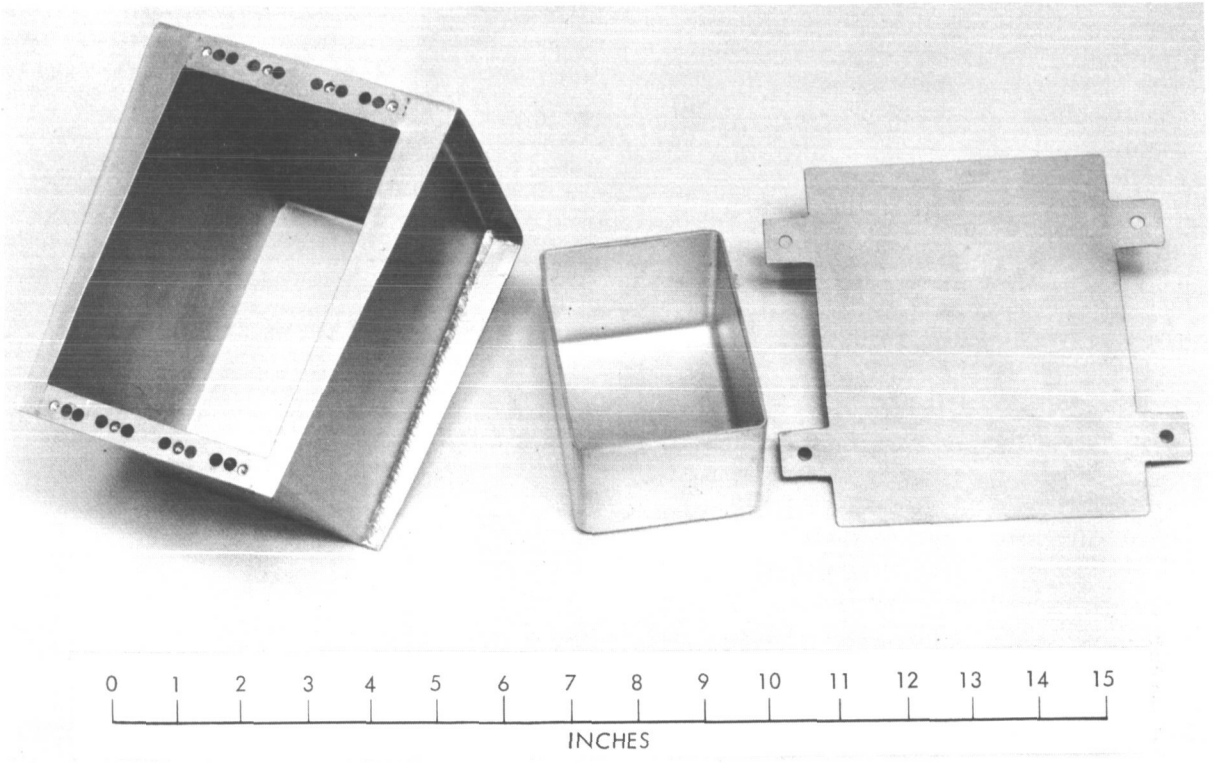

FIGURE 2.—Formed and welded deep-drawn box of gold electroplate over electroless nickel with an electroless nickel cover.

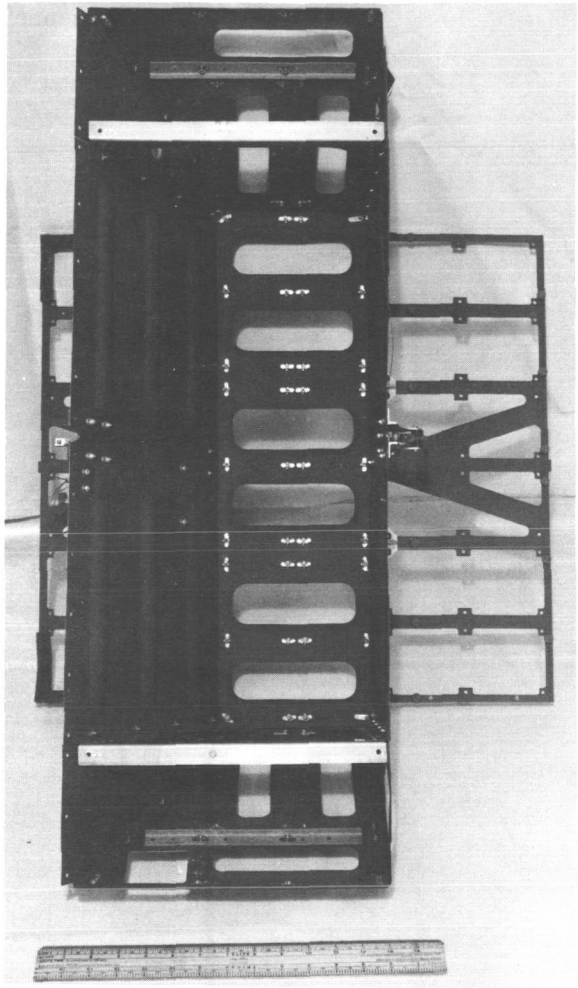

FIGURE 3.—Satellite unit of 0.020-inch thick LA141A sheet.

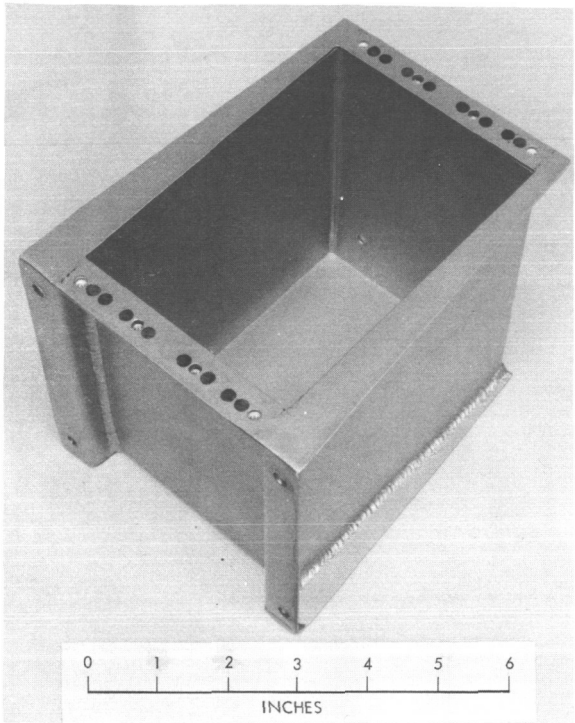

FIGURE 4.—Component severely formed, welded, Dow-17 coated, and painted.

NONAEROSPACE USES

Because of their lightness, there is reason to believe that magnesium-lithium alloys can compete in certain nonaerospace applications. Currently, the aircraft industry appears to be the most logical user. Expected applications will be brackets, mounts, boxes for electronic equipment, trim, and other nonstructural components comparable with current aerospace parts.

Table 1 lists some comparative characteristics of the commercial magnesium-lithium alloy, LA141A; the aluminum alloys, 6061–T4 and 6061–T6; the magnesium alloy, AZ31B; and a glass-fiber-reinforced plastic. In general, these materials are applicable for use in nonstructural aircraft components requiring maximum formability and resistance to corrosion.

These data indicate that, although the magnesium-lithium alloys do not exhibit an attractive strength-to-weight ratio, they do exhibit an outstanding modulus- or stiffness-to-density ratio. It is to this latter criterion that many nonstructural aircraft components are designed.

Currently, LA141A alloy is being considered for various components in the new C5A military transport. Potential applications include lining for the cargo compartment, brackets, stiffeners, unused packaging, emergency ladders, fairings, and emergency-access doors. Several aircraft companies have expressed interest in these alloys; however, no specific applications have developed to date.

To make these alloys more attractive to aircraft designers, further research is needed. Of particular importance is the development of fabrication techniques for producing rigidized structures. Such structures would include honeycomb, perforated, embossed, chem-milled,

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TABLE 1.—*Comparative Properties of Some Nonstructural Aircraft Materials*

Materials	Ultimate tensile strength, psi	Ultimate tensile strength-to-density ratio, in.	Yield tensile strength, psi	Yield tensile strength-to-density ratio, in.	Modulus of elasticity, psi$\times 10^6$	Modulus of elasticity-to-density ratio, in.$\times 10^6$	Elongation, %	Density, lb/in.^{3}
Magnesium-lithium alloy:								
LA141A–T7	21 000	430 000	18 000	370 000	6. 1	125	24	0. 049
Aluminum alloy:								
6061–T4	35 000	350 000	21 000	210 000	10	100	22	. 098
6061–T6	45 000	460 000	40 000	410 000	10	100	12	. 098
Magnesium alloy:								
AZ31B–O	37 000	580 000	22 000	340 000	6. 5	100	21	. 064
AZ31B–H	42 000	660 000	32 000	500 000	6. 5	100	15	. 064
Glass-fiber-reinforced plastic Stratiglas	80 000	1 000 000	----------	----------	4	51	----------	. 078

or machined components. The availability of rigidized alloy components could result in substantial weight savings in new aircraft.

Electrical and vibrational characteristics of the alloys may also be of interest. For electrical equipment in aircraft, resistivity and conductivity are sometimes compared on a weight basis, which would weigh in favor of these alloys. In resonance applications, they also compare favorably with the standard magnesium alloys. Some change in resonant frequency (up to 10 percent) can be obtained by substituting magnesium-lithium alloys for magnesium alloys. This frequency shift may be helpful in reducing vibration stresses where standard magnesium or aluminum parts in a structure have a resonant frequency within the critical range.

In addition to aircraft uses, a lightweight armor application for these alloys remains a possibility because of ballistic characteristics. In 1957 the U.S. Army began development of such alloys for use in armored vehicles. As a result, an experimental magnesium-lithium hull for the M113 armored personnel carrier was fabricated (fig. 5). This hull has been extensively evaluated and road tested and found satisfactory. However, in the fabrication of the hull, difficulties were encountered in producing high-quality plate and in welding thick plate. High cost was also a factor. The commercial development of LA141A in recent years has done much to alleviate these difficulties. Thus, it is possible that magnesium-lithium alloys will again find armor applications.

Backing for certain ceramic armors used in helicopters is also a possibility. Currently, glass fiber-reinforced plastic and aluminum are being used and, even though the alloys are being considered, none have been evaluated.

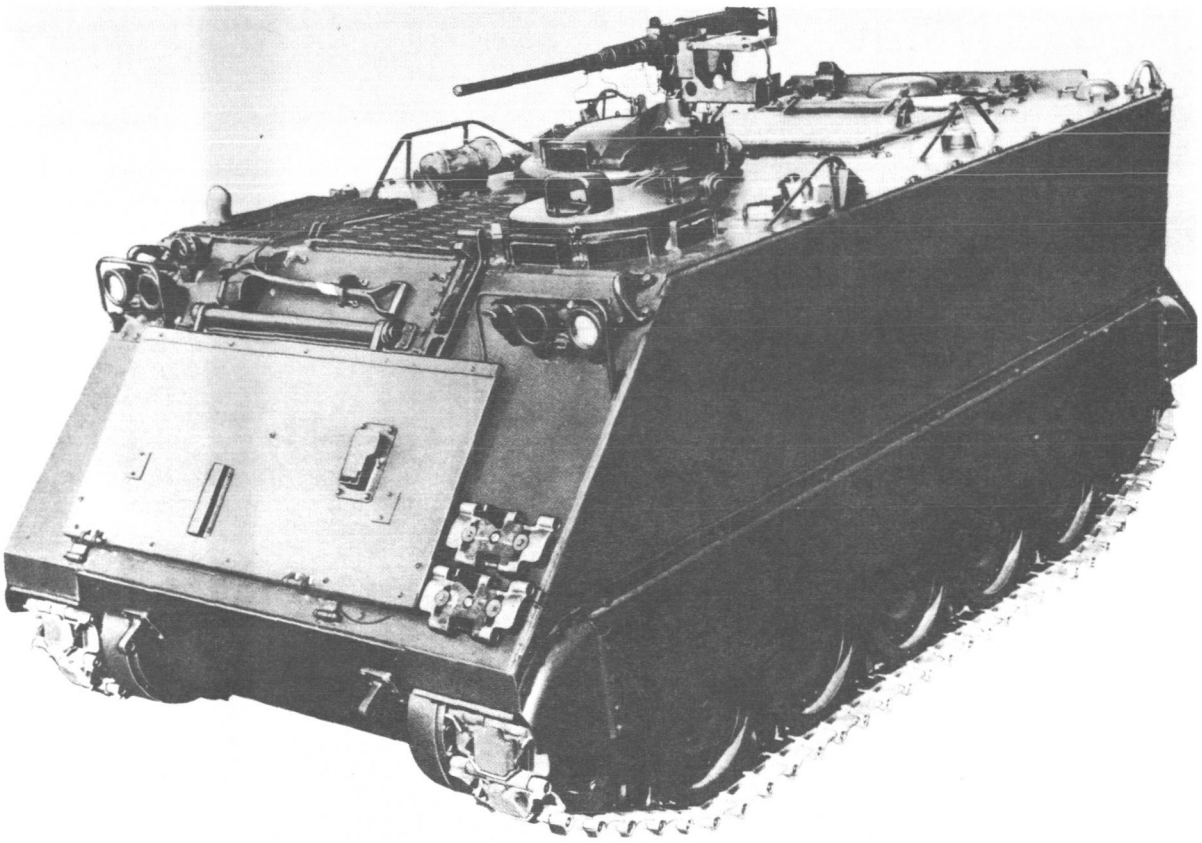

FIGURE 5.—M113 armored personnel carrier.

The magnesium-lithium alloys and their fabrication costs are considerably less expensive than beryllium and its alloys. However, concerning applications that are competitive by today's standards, it is impossible to predict with any accuracy the extent to which the alloys will be used. They are not expected to compete extensively with conventional magnesium or aluminum alloys in automobiles, building construction, or appliances in the foreseeable future. Cost is the primary factor, and there is little possibility that the cost of magnesium-lithium alloys will reach that of magnesium or aluminum. Therefore, only where properties are more important than cost will they find favor.

Alloy Designations

Currently, five magnesium-lithium alloys are available for applications in aerospace vehicles. The designations, nominal chemical compositions, and developmental status of these alloys are indicated in table 2. Of these alloys, only LA141A is currently sold as a commercial material. The others must be obtained from producers on a custom-order basis or from laboratories on a research basis.

PRODUCERS AND FORMS AVAILABLE

Magnesium-lithium alloys have been produced in sheet, plate, foil, extrusions, forgings, wire, and castings. Currently, Battelle Memorial Institute is developing for Marshall Space Flight Center, NASA, a process for adhesive bonding of LAZ933A honeycomb structures (ref. 7).

Brooks and Perkins (B&P), Detroit, Mich., is the major producer of magnesium-lithium alloys and can supply LA141A in a complete product line including ingots, sheet and plate, extrusions (both solid and hollow), castings, welding wire, and powder (ref. 11). Also, forgings and foil are available on specific request.

Wellman Dynamics Corp. (formerly Wellman Bronze and Aluminum Co.) produces magnesium-lithium sand castings. This company specializes in quality sand castings for the aerospace industry which are available on special request.

The only other producer for magnesium-lithium alloys at this time is Magnesium Elektron, Ltd. (MEL), Manchester, Eng., which has an American sales subsidiary, Magnesium Elektron, Inc., in New York City. MEL produces magnesium-lithium alloys on a very small scale on custom orders.

SPECIFICATIONS

Only one magnesium-lithium alloy, LA141A, is covered by the specifications defined as follows:

(1) Aerospace Material Specification AMS 4386, June 30, 1964

(2) Brooks and Perkins, Inc., Specification BP-S-125 Revision B magnesium-lithium alloy LA141A sheet and plate

(3) IBM, Federal Systems Division Specification 6009417

(4) Lockheed Missiles and Space Company LAC 07-4194A, Dec. 26, 1963.

Since the four specifications are essentially the same, only AMS 4386 is included in appendix B.

TABLE 2.—*Magnesium-Lithium Alloys of Current Interest* [a]

Alloy designation	Nominal composition, weight %	Development status
LA141A	Mg-14Li-1Al	Commercial alloy.
LA91A	Mg-9Li-1Al	Experimental (Battelle-NASA).
LAZ933A	Mg-9Li-3Al-3Zn	Experimental (Battelle-NASA).
None	Mg-14Li-0.5Si	Experimental (Frankford Arsenal).
None	Mg-14Li-3Ag-5Zn-2Si	Experimental (Frankford Arsenal).

[a] Ref. 1.

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CHAPTER 3

Mechanical Properties

Magnesium-lithium alloys are not outstandingly strong. However, they are the lightest metallic materials now commercially available. Also, they have elastic moduli equivalent to those of commercial magnesium alloys. This combination of lightness and stiffness is the major characteristic making them attractive for aerospace vehicles.

TENSILE PROPERTIES

The wrought magnesium-lithium alloys of current interest have room-temperature properties approximating those of the magnesium sheet alloy M1A or the low-strength aluminum alloy 5052–0. As castings, however, the magnesium-lithium alloys exhibit strengths comparable to many of the commercial magnesium and aluminum sand-casting alloys. NASA is sponsoring research directed toward development of stronger magnesium-lithium alloys with the following target properties: (1) 45 000 psi ultimate tensile strength, (2) 35 000 psi yield tensile strength, and (3) 20 percent elongation.

These values, except the one for elongation, are specified for the temperature range from 68° to −423° F (ref. 10). Alloys of these strength levels at these temperatures have been made in the past but the properties are not stable above room temperature. Appendix A summarizes the development of magnesium-lithium alloys.

Design Data

Currently, design data are available only for the LA141A alloy. Table 3 contains the minimum specified tensile properties for sheet and plate.

These properties are for the alloy in the T7 stabilized condition as specified in AMS 4386, June 30, 1964. This treatment consists of heating for 3 to 6 hours at 350° F.

TABLE 3.—*Guaranteed Minimum Specified Tensile Properties of LA141A–T7 Sheet and Plate*

Nominal thickness, in.	Ultimate tensile strength, psi	Yield tensile strength, psi	Elongation, %
0.010 to 0.090	19 000	15 000	10
0.090 to 0.250	19 000	14 000	10
0.250 to 2.000	18 000	13 000	10

TABLE 4.—*Design Tensile Properties of LA141A for Short-Time Stress* [a]

Temperature, °F	Ultimate tensile strength, psi	Yield tensile strength, psi	Elongation, %
−320	26 000	21 000	10
−110	25 000	20 000	10
0	23 000	19 000	10
Room	19 000	15 000	12
150	12 000	9 000	15
200	8 000	6 000	20
250	6 000	4 000	25

[a] LMSC data.

Table 4 presents design data for LA141A at elevated and cryogenic temperatures for sheet up to 0.090 inch thick.

Typical Data

Tensile data are available for LA141A sheet, plate, extrusions, and castings, and somewhat more limited data are available for the semicommercial alloys, as shown in table 5.

Figures 6, 7, and 8 depict the tensile properties of magnesium-lithium alloys at temperatures between 300° and −400° F. These data

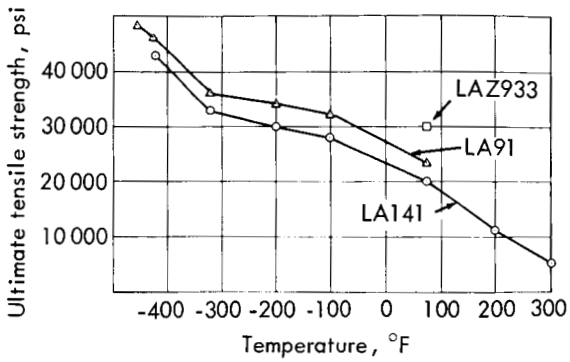

FIGURE 6.—Ultimate tensile strength versus temperature for magnesium-lithium alloys.

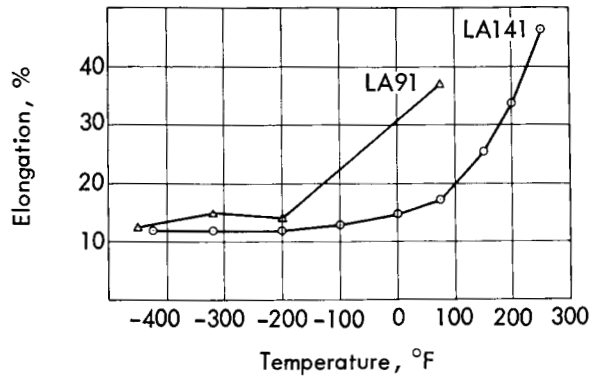

FIGURE 8.—Elongation versus temperature for magnesium-lithium alloys.

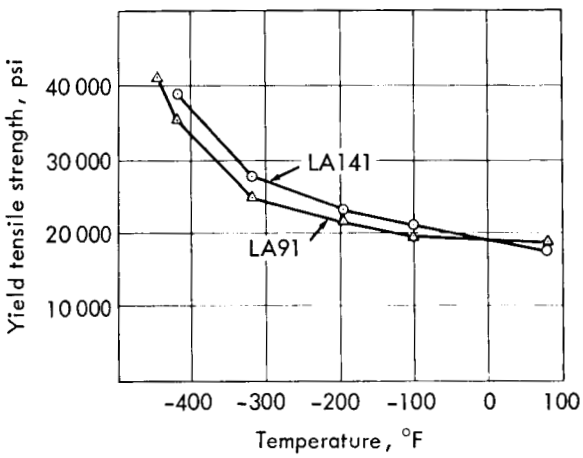

FIGURE 7.—Yield tensile strength versus temperature for magnesium-lithium alloys.

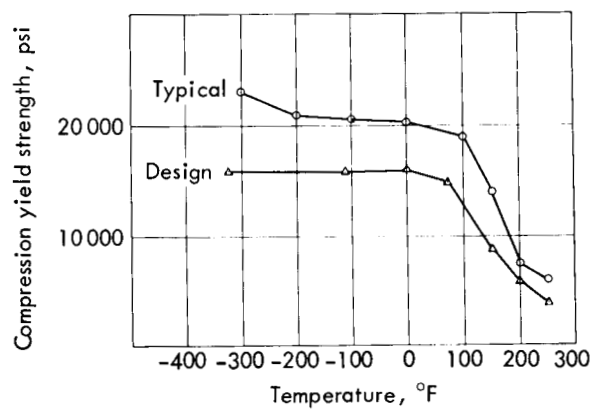

FIGURE 9.—Compression yield strength versus temperature for LA141A.

indicate that the magnesium-lithium alloys do not exhibit brittle characteristics at cryogenic temperatures and, thus, could be considered for tankage at the liquid-hydrogen temperature. However, they lose strength at even moderately elevated temperatures and are not normally considered for elevated-temperature applications.

COMPRESSION STRENGTH

Design and typical compression yield strengths for LA141A in most cases as annealed sheet at temperatures between 250° and −320° F are depicted in figure 9.

Magnesium-lithium alloys, unlike most conventional magnesium alloys, exhibit compression yield strengths comparable to their tensile yield strengths. However, at cryogenic temperatures the tensile/compression yield ratio is less than unity, but at elevated temperatures the ratio is close to unity.

BEARING STRENGTH

Table 6 lists design and typical values of bearing strength for LA141A annealed sheet.

FATIGUE STRENGTH

Figures 10 and 11 depict fatigue data for bare, welded, and coated LA141 sheet material. The alloy's endurance limit at 10^8 cycles is 8000 psi.

TABLE 5.—*Typical Tensile Properties of Magnesium-Lithium Alloys at Room Temperature*

Alloy designation	Ultimate tensile strength, psi	Yield tensile strength, psi	Elongation, %	Source
LA141A:				
Sheet and plate	21 000	17 000	27	NASA [a]
	21 800	19 500	17	Brooks & Perkins [b]
	21 000	18 000	24	LMSC
Extrusion	20 200	15 700	22	Brooks & Perkins [b]
Casting	17 700	12 300	17	Brooks & Perkins [b]
LA91A:				
Sheet and plate	22 000	16 500	30	NASA [a]
LAZ933A:				
Sheet and plate	30 000	21 000	30	NASA [c]
Mg–14Li–0.5Si:				
Casting	19 750	17 000	23	Frankford Arsenal [d]
Wrought	20 200	17 200	35	
Mg–14Li–5Zn–3Ag–2Si:				
Casting	29 000	25 000	5	Frankford Arsenal [d]
Wrought	29 100	26 500	37	

[a] Ref. 12.
[b] Ref. 11.
[c] Ref. 13.
[d] Ref. 5.

TABLE 6.—*LA141A Alloy Transverse and Longitudinal Bearing Strength* [a]

Temperature, °F	Bearing strength, psi			
	Ultimate		Yield	
	Design	Typical	Design	Typical
Room temperature	43 000	----------	27 000	----------
Longitudinal	----------	46 500	----------	31 000
Transverse	----------	46 400	----------	33 000
150°	28 000	----------	22 000	----------
Longitudinal	----------	30 600	----------	26 000
Transverse	----------	30 100	----------	24 700

[a] LMSC data.

IMPACT STRENGTH

Specific data for LA141A are listed in table 7. Magnesium-lithium alloys exhibit surprisingly high impact strengths. In general, their Charpy V-notch values are an order of magnitude greater than those for conventional magnesium alloys. This characteristic relates to their excellent ballistic properties and augurs well for their use in space vehicles as meteoroid shielding.

CREEP STRENGTH

Data on creep for LA141A are presented in figures 12 and 13. The creep strength of magnesium-lithium alloys is poor. In general, they should not be considered as load-bearing materials at elevated temperatures.

TABLE 7.—*Charpy Impact (V-Notch) Toughness of LA141A Alloy* [a]

Temperature, °F	Surface notch		Short transverse notch	
	Longitudinal, ft-lb	Transverse, ft-lb	Longitudinal, ft-lb	Transverse, ft-lb
−320	15	31	11	15
−110	15	30	9	14
−20	15	30	9	15
+75	15	32	10	14
+150	14	28	9	15

[a] LMSC data.

ELASTIC MODULUS

Figure 14 indicates the elastic modulus for several alloys. Typical modulus values for LA141A, LAZ933A, and LA91A are listed in table 8. Magnesium-lithium alloys exhibit a modulus of elasticity about equal to that for conventional magnesium alloys. However, their density is 20 to 25 percent lower than the density of other magnesium alloys. Thus, most aerospace components designed on a modulus-to-density basis will be significantly lighter when made of magnesium-lithium alloys than when made of conventional alloys.

Some elastic modulus values for LA141A at various temperatures are listed in table 9.

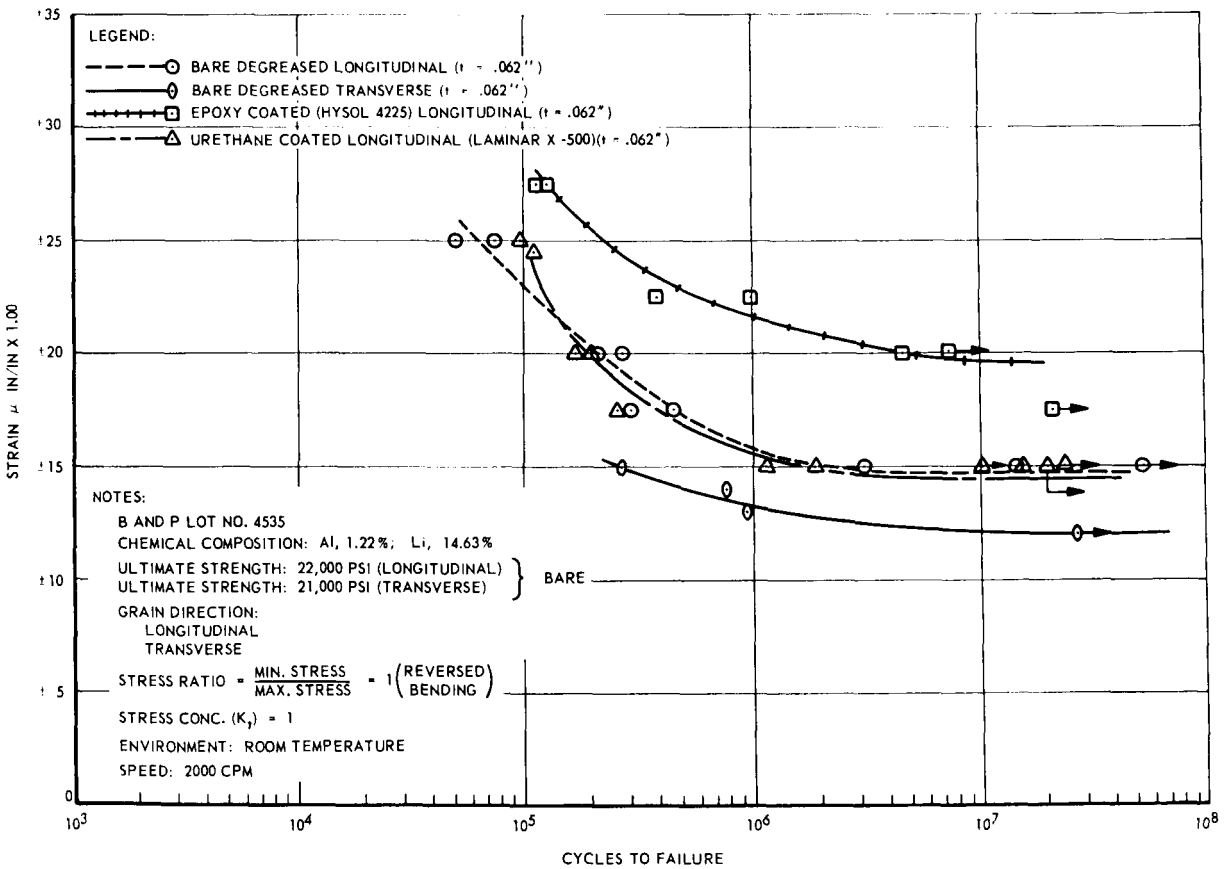

FIGURE 10.—Fatigue data on LA141A with various coatings. (IBM data.)

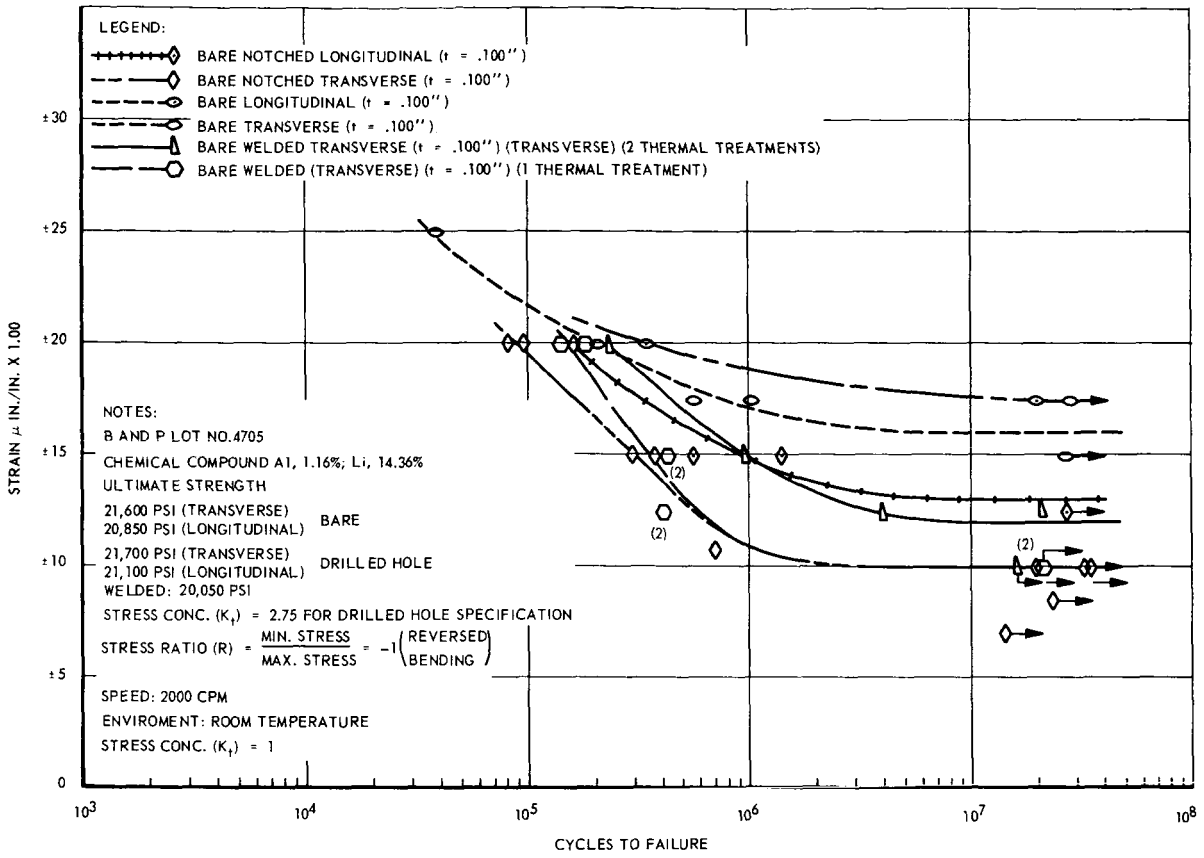

FIGURE 11.—Fatigue data on LA141A, bare. (IBM data.)

TABLE 8.—*Typical Modulus Values for Magnesium-Lithium Alloys*[a]

Alloy designation	Modulus of elasticity, psi×10^6
LA141A	6.2
LAZ933A	6.4
LA91A	6.6

[a] Battelle data.

This modulus of elasticity is somewhat anisotropic. Values for sheet are higher in the direction transverse to the rolling directions. This anisotropy suggests that designers should consider placing critical stresses along the transverse sheet direction (ref. 9).

TABLE 9.—*Elastic Modulus of LA141A at Various Temperatures*[a]

Temperature, °F	Elastic modulus, psi×10^6
−105	7.2
+70	5.6–6.2 longitudinal
+70	6.0–6.7 transverse
+150	5.0
+250	3.4
+300	2.6

[a] Brooks and Perkins Co. data.

HARDNESS

Representative R_E hardness values are 65 for LA141A, 55 for LA91A, and 79 for LAZ933A.

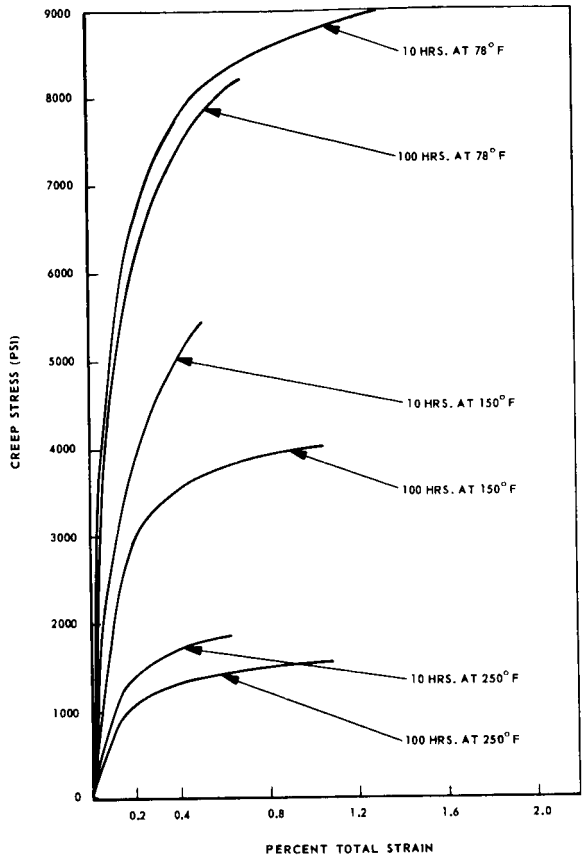

FIGURE 12.—LA141A magnesium-lithium alloy sheet (0.063-inch thick), typical creep stress versus strain. (Dow Metal Products Co. data.)

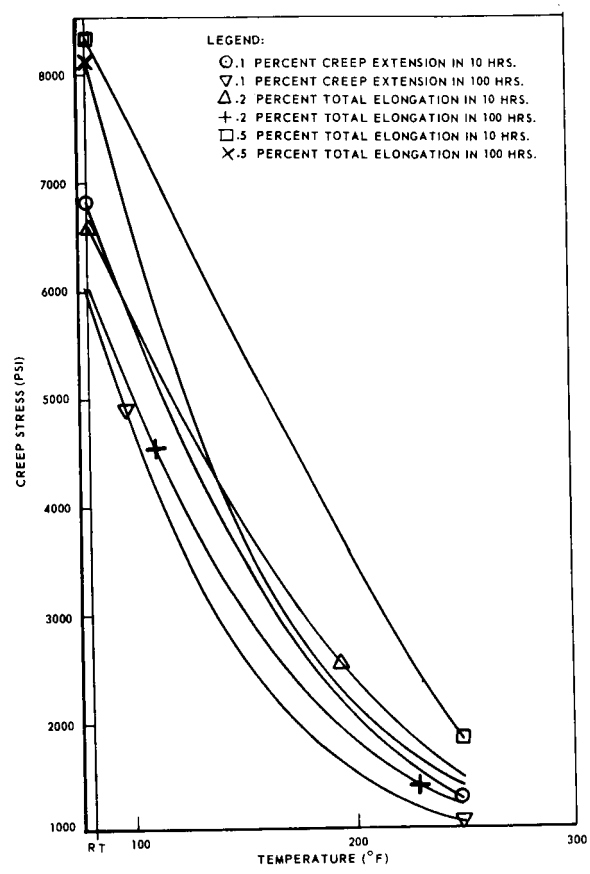

FIGURE 13.—LA141A magnesium-lithium alloy sheet, typical creep strength versus temperature. (Dow Metal Products Co. data.)

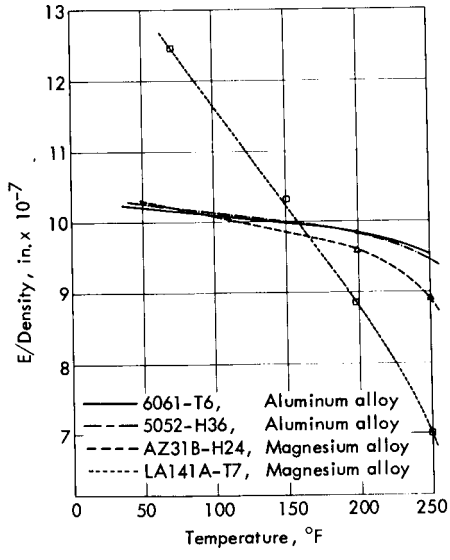

FIGURE 14.—Tensile modulus density versus temperature. (IBM data.)

CHAPTER 4

Physical and Metallurgical Properties

Most of the metallurgical and physical properties of magnesium-lithium alloys resemble those of conventional magnesium alloys. However, the densities differ significantly, the magnesium-lithium alloys being 25 percent lighter. Also, the basic metallurgical structure of magnesium-lithium alloys is different from that of magnesium. They exhibit a body-centered cubic structure whereas the magnesium structure is hexagonal. This difference has a striking effect on the fabrication characteristics of magnesium-lithium alloys.

DENSITY

Table 10 lists density and specific gravity values for magnesium-lithium alloys.

TABLE 10.—*Density and Specific Gravity Values for Magnesium-Lithium Alloys* [a]

Alloy designation	Density, lb/in.^{3}	Specific gravity
LA141A	0. 049	1. 35
LA91A	. 053	1. 45
LAZ933A	. 057	1. 56
Mg–14Li–0.5Si	. 048	1. 33
Mg–14Li–5Zn–3Ag–2Si	. 054	1. 49

[a] Ref. 1.

MELTING POINT

The melting point for the commercial alloy LA141A is about 1075°±10° F (ref. 9). No data are available for other magnesium-lithium alloys.

STRUCTURE

Magnesium-lithium phase relationships have been studied by many investigators. The most widely used diagram has been that of Grube (ref. 14), shown in figure 15. However, in 1954, Freeth and Raynor (ref. 15) redetermined the binary diagram as shown in figure 16.

At present, the body-centered cubic structure of all-beta alloys (particularly LA141A alloy) containing approximately 14 percent lithium is of greatest interest. Some representative microstructures of all-beta alloys (LA141A, Mg–14Li–0.5Si, and Mg–14Li–5Zn–3Ag–2Si) are shown in figures 17, 18, and 19. In these alloys, the matrix is a magnesium-lithium solid solution. Various secondary phases containing aluminum, zinc, silver, or silicon may also be seen in the microstructures. These alloys exhibit extreme lightness and excellent ductility.

Magnesium-lithium alloys containing such hardening additions as aluminum, zinc, silver, or cadmium can be strengthened by heat treatment. Early work at Battelle (ref. 22) showed that ultimate tensile strengths over 45 000 psi, yield tensile strengths over 35 000 psi, and elongations over 10 percent were obtainable. Unfortunately, the strength diminished gradually above 150° F because of diffusion and precipitation of the alloying elements. This tendency to lose strength at relatively low temperatures has been studied by many investigators but has not yet been overcome.

The major precipitating phase in heat-treatable magnesium-lithium alloys has been identified as $MgLi_2X$ where X represents any of the elements zinc, cadmium, aluminum, or silver. This compound, or theta phase, is not stable but transforms on overaging at low temperatures to an equilibrium phase, which does not contribute to strength. As a consequence of the overaging, the commercial alloys are currently not used in a high-strength condition but are used in a soft, annealed condition.

The recent development of the higher-strength LAZ933A alloy has directed interest

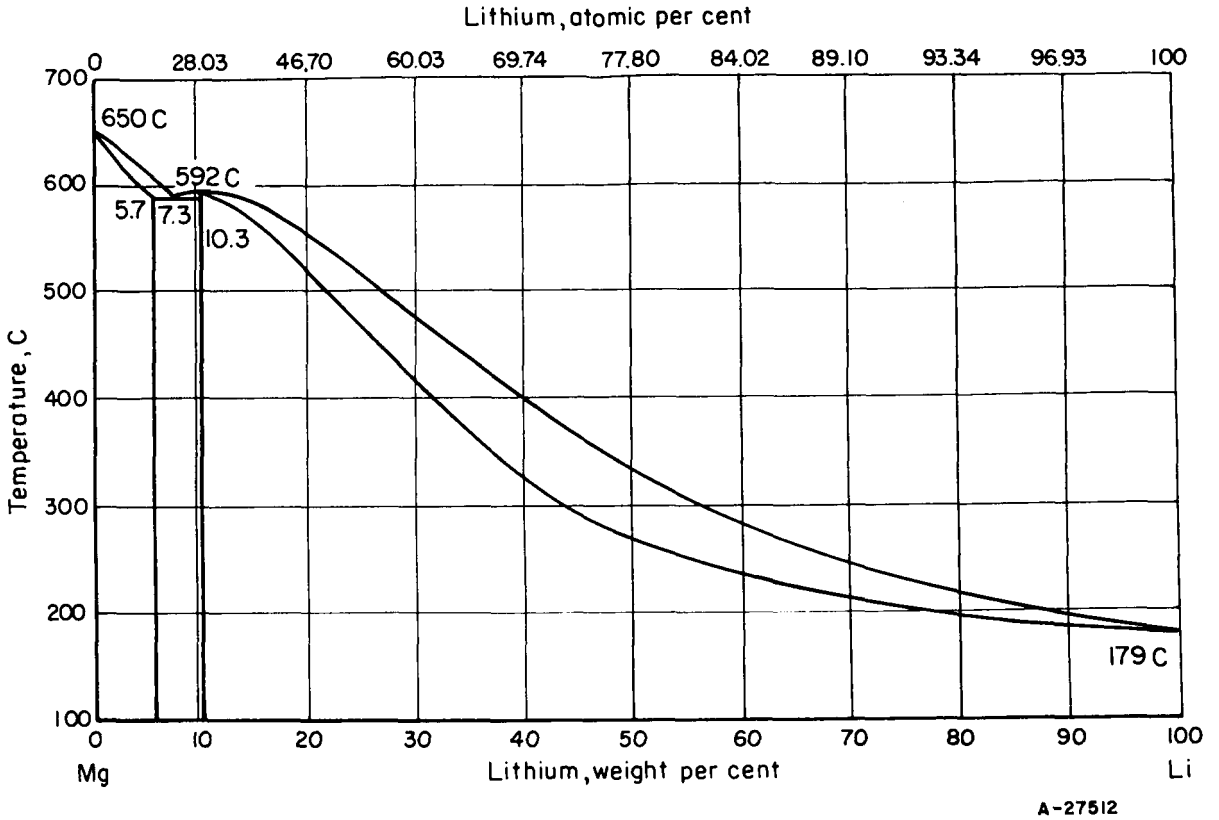

FIGURE 15.—Magnesium-lithium equilibrium diagram from Grube (ref. 14).

to the alpha-plus-beta magnesium-lithium alloys. Representative microstructures for LAZ933A and LA91A are shown in figures 20 and 21. The structures consist of a mixture of an alpha phase, which is a magnesium-rich solid solution, and a beta phase, which is a lithium-rich solid solution. The beta phase, being the matrix, imparts ductility. These alpha-plus-beta alloys, as the all-beta alloys, can be significantly strengthened by heat treatment.

THERMAL, ELECTRICAL, AND OTHER PROPERTIES

The alloy LA141A is typical of magnesium-lithium alloys with respect to its thermal and electrical characteristics. Tables 11 and 12 detail the data available for LA141A. Comparative data for other alloys were not available at the time of publication.

TABLE 11.—*Electrical Characteristics of LA141A*

Electrical resistivity, μΩ/cm at 75° F	15.2
Electrical conductivity, mass (% IACS at 75° F)	75.3
Volume (% IACS at 75° F)	11.4

TABLE 12.—*Thermal Characteristics of LA141A* [a]

Temperature, °F	Thermal conductivity, BTU/ft²/in./°F/hr	Specific heat, BTU/lb
75	301	0.346
100	298	.346
200	290	.347
300	287	.348
400	282	.350
500	280	.350

[a] Melting point has been previously stated.

To determine the effects of vacuum exposure upon LA141A, a specimen was exposed to a vacuum environment of 2×10^{-7} mm Hg at

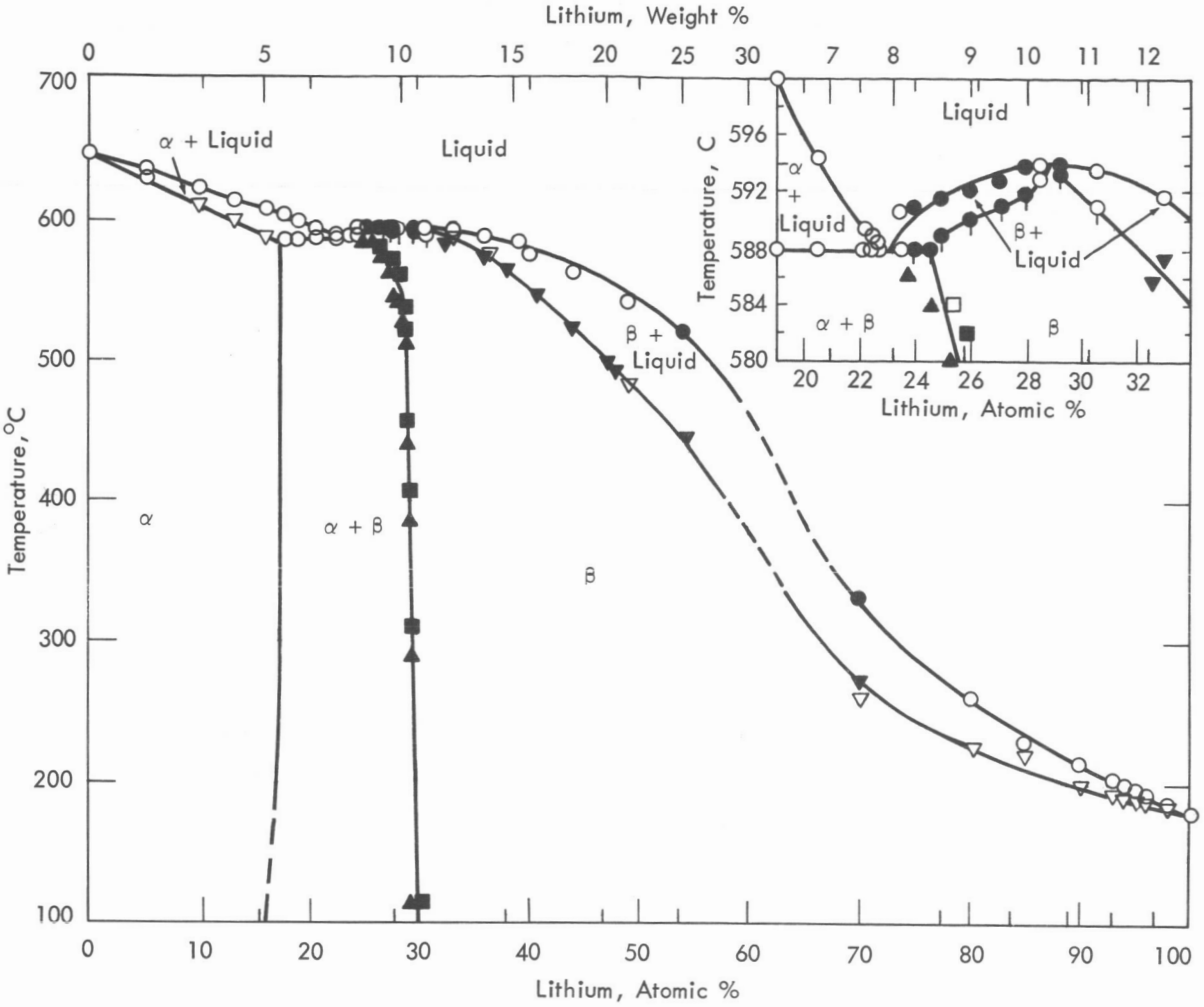

FIGURE 16.—Magnesium-lithium phase diagram from Freeth and Raynor (ref. 15).

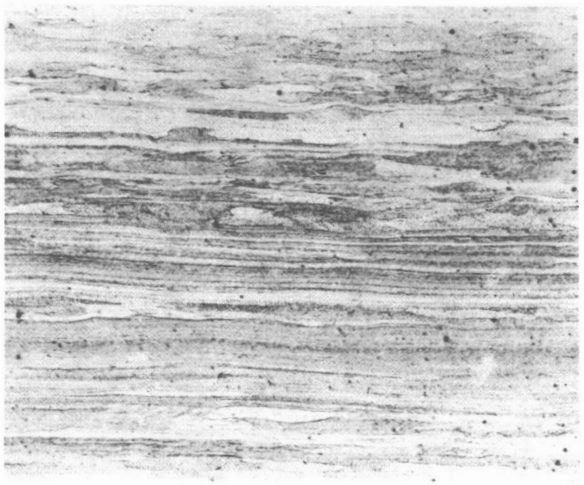

FIGURE 17.—Microstructure of LA141A alloy in as-rolled condition (550° F).

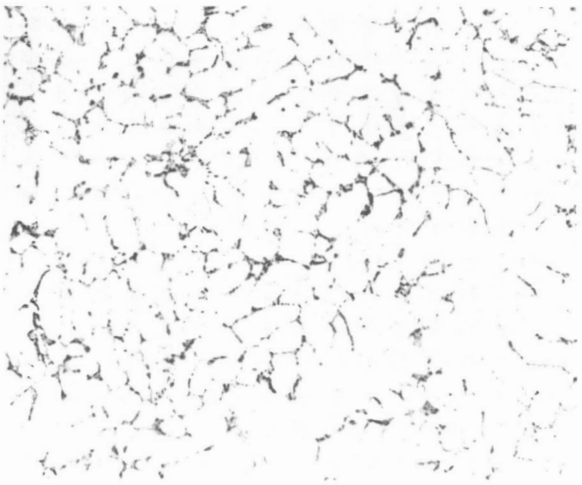

FIGURE 18.—Microstructure of Mg-14Li-0.5Si in as-cast condition.

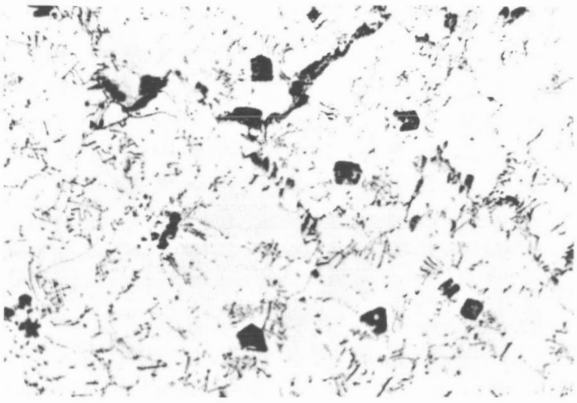

FIGURE 19.—Microstructure of Mg-14Li-5Zn-3Ag-2Si alloy in as-cast condition.

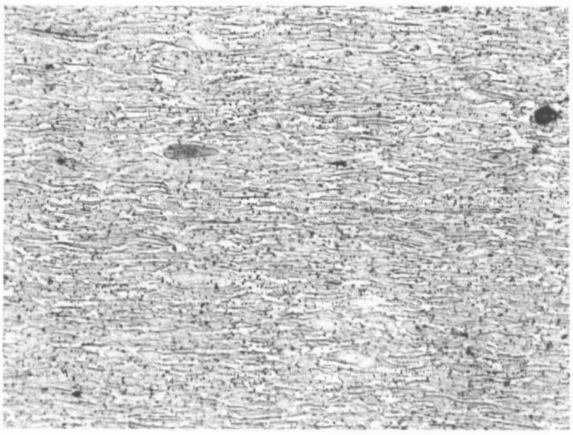

FIGURE 20.—Microstructure of LAZ933A alloy in as-rolled condition.

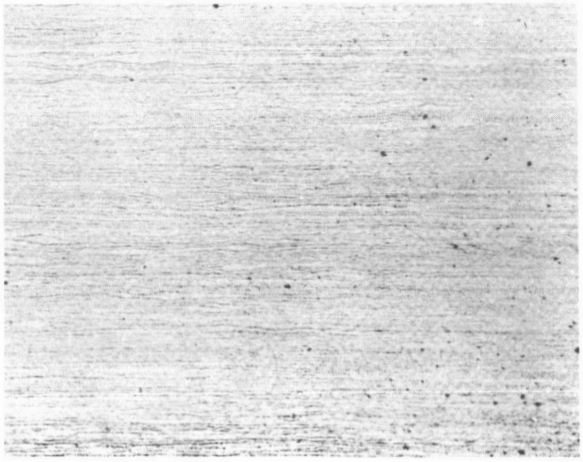

FIGURE 21.—Microstructure of LA91A alloy in as-rolled condition.

400° F for 55 hours. The specimen showed no loss of weight due to sublimation.

The thermal expansion characteristics of LA141A are shown in table 13.

TABLE 13.—*Thermal Expansion Characteristics of LA141A*

Temperature range, °F	Coefficient of expansion
−200 to +75	0. 0000215
75 to 200	. 0000218
75 to 400	. 0000222

CHAPTER 5

Meteoroid Resistance

Since magnesium-lithium alloys exhibit excellent resistance to penetration by low-velocity fragments, they were extensively evaluated for lightweight armor material. Research carried on for a number of years on lightweight aircraft armor showed that the magnesium-lithium alloys containing around 13 to 14 percent lithium plus 1 to about 6 percent aluminum had excellent armor characteristics. On a weight basis, they afford better protection against low- and intermediate-velocity fragments than any other metallic materials studied to date. These alloys, however, are not suitable as armor for projectiles of .30 caliber and larger.

Considering the good penetration resistance of magnesium-lithium alloys, it is not surprising that they also exhibit outstanding resistance to hypervelocity particles, such as meteoroids. Theoretical impact data for LA141A and other materials are shown in table 14.

TABLE 14.—*Theoretical Impact Data for Various Aerospace Materials* [a]

Material	Density, lb/in.^{3}	Unit weight required
Aluminum, 2219–T87	0.100	1
Magnesium, AZ80A	.065	0.81–0.87
Magnesium, LA141A	.049	0.67–0.77
Fiberglas	.071	0.84–0.89
Fortisan (rayon)	----------	0.70–0.80
Titanium, 6A1–4V	.161	1.17–1.27

[a] Convair data; ref. 17.

These data indicate that the low-density, magnesium-lithium alloy LA141A would save 20 to 38 percent of a spacecraft hull weight, compared with an equivalent meteoroid-protection system using aluminum.

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CHAPTER 6

Joining

Magnesium-lithium alloys are readily joined by the common techniques of fusion welding, resistance welding, and adhesive bonding. In addition, some development work has been directed toward soldering, brazing, and electron-beam welding.

FUSION WELDING

Magnesium-lithium alloys can be readily joined by conventional fusion-welding techniques. Joint efficiencies are high and weld-cracking difficulties are rare. Sheet thicknesses that are commonly welded range from 0.040 to 0.090 inch.

Sheet and plate have been readily joined by automatic and semiautomatic welding. Both the tungsten-inert gas (TIG) and metal-inert gas (MIG) processes are applicable. The use of helium gas maintains a cleaner appearance of the liquid pool. However, by using argon gas, weldments with 100 percent joint efficiency have been obtained. Backside shielding is required to reduce underside oxidation. Figure 22 shows a pressure vessel fusion-welded from two magnesium-lithium alloys, LA141A and LA91A. Welding was done by the MIG process using EZ33A filler. This vessel was fabricated by NASA to demonstrate the feasibility of using magnesium-lithium alloys in fusion-welded, space-vehicle components.

Prior to welding, magnesium-lithium alloys must be carefully cleaned. For mechanical cleaning, stainless-steel or aluminum-wire brushing, or aluminum-oxide abrasive can be used successfully. Steel wool, steel-wire brushes, or emery cloth should not be used and chemical cleaning is normally not used because of excessive chemical reaction and subsequent surface oxidation. Welding should be performed not later than 30 minutes after cleaning.

Magnesium-lithium alloys need not be preheated. However, weldments usually require a post-weld stress relief at temperatures between 250° and 350° F.

A number of filler metals have been used successfully to fusion-weld magnesium-lithium alloys. Welding wire of LA141A is available from Brooks and Perkins Co. in 0.045-, 0.062-, and 0.093-inch gages. In addition, EZ33A, AZ92A, and AZ61A have also been used. As with the base material, it is necessary to use freshly cleaned welding wire which can be cleaned by passing through stainless-steel wool.

Although all the currently available magnesium-lithium alloys have been successfully fusion-welded, by far the greatest amount of mechanical-property data are available for LA141A, which are shown in table 15. Alloy LA141A weldments exhibit almost 100 percent joint efficiency. Properties of these alloys are not sensitive to welding variables, changes in sheet thicknesses, or filler materials. At cryogenic temperatures, the strengths and ductilities are attractive enough to justify the use of the

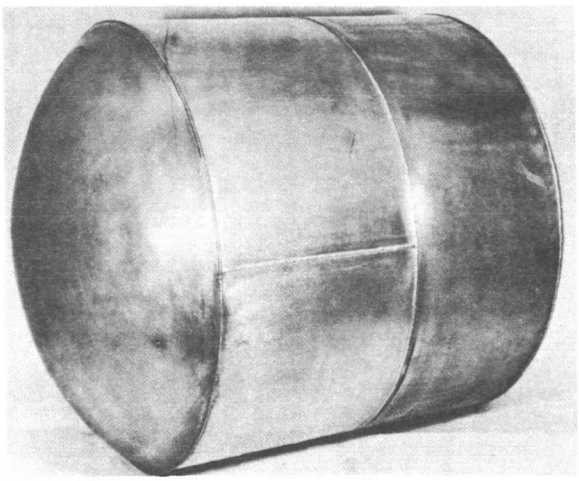

FIGURE 22.—Vessel fabricated at NASA from LA141A and LA91A alloys. (Cylindrical section measures 30 inches in diameter and 30 inches deep.)

TABLE 15.—*Mechanical Properties of LA141A Magnesium-Lithium Alloy Weldments*

Base materials	Filler metal	Test temperature, °F	Ultimate tensile strength, psi	Yield tensile strength, psi	Elongation in 2 in., %	Welding method	Inert gas	Stress relief		Sheet thickness, in.
								Temp, °F	Time, hr	
LSMC data										
LA141A−LA141A	AZ61A	70	20 600	16 200	17. 9	TIG	Argon	300	24	0. 063
	AZ92A	70	21 100	18 300	17. 3	TIG	Argon	300	24	. 063
	EZ33A	70	21 600	18 800	7. 3	TIG	Argon	300	24	. 063
	None	70	20 000	18 000	16. 7	TIG	Argon	300	24	. 063
	AZ61A	150	14 200	8 400	26. 5	TIG	Argon	300	24	. 063
	AZ92A	150	15 300	11 400	21. 5	TIG	Argon	300	24	. 063
	EZ33A	150	11 500	10 100	10. 1	TIG	Argon	300	24	. 063
	None	150	14 000	11 000	27. 4	TIG	Argon	300	24	. 063
	AZ61A	250	9 300	5 000	39. 4	TIG	Argon	300	24	. 063
	AZ92A	250	8 900	4 900	41. 4	TIG	Argon	300	24	. 063
	EZ33A	250	9 300	4 600	17. 8	TIG	Argon	300	24	. 063
	None	250	8 300	4 600	32. 4	TIG	Argon	300	24	. 063
LA141A+HM21A-T8	EZ33A	70	17 700	21 700	9. 8	TIG	Argon	300	24	. 063
LA141A+AZ31B-0	AZ92A	70	22 300	18 600	5. 9	TIG	Argon	300	24	. 063
	EZ33A	70	20 000	17 800	14. 4	TIG	Argon	300	24	. 063
IBM data										
LA141+LA141	LA141	70	20 500	----------	11. 3	----------	Argon	390	1	. 050
	LA141	70	20 900	----------	6. 7	Heliarc	Helium	390	1	. 047
	HK31	70	21 600	----------	9. 5	----------	Argon	390	1	. 049
	HK31	70	19 800	----------	7	Heliarc	Helium	390	1	. 051
	LA141	70	22 500	----------	5. 7	----------	Argon	390	1	. 052
	LA141	70	22 900	----------	5. 7	Heliarc	Helium	390	1	. 050
LA141+AZ31	HK31	70	22 900	----------	6. 7	----------	Argon	390	1	. 050
	HK31	70	20 800	----------	4. 7	Heliarc	Helium	390	1	. 049
	AZ92	70	21 600	----------	5. 7	----------	Argon	390	1	. 049
	AZ92	70	20 900	----------	7. 2	Heliarc	Helium	390	1	. 050
LA141+LA141	EZ33	70	18 800	----------	4	Heliarc	Helium	390	1	. 052
LA141+AZ31	EZ33	70	20 200	----------	2. 6	Heliarc	Helium	390	1	. 052
NASA data										
LA141+LA141	EZ33A	75	18 700	17 900	17. 8	TIG	----------	None	--------	. 090
	EZ33A	−100	24 900	17 900	8. 2	TIG	----------	None	--------	. 090
	EZ33A	−200	26 000	18 800	8. 2	TIG	----------	None	--------	. 090
	EZ33A	−320	28 900	24 600	8. 7	TIG	----------	None	--------	. 090
	EZ33A	−423	41 900	31 200	3. 3	TIG	----------	None	--------	. 090

alloy in space-vehicle structures that are moderately loaded. However, properties of weldments at elevated temperatures are poor.

Mechanical properties for repair welds using manual, tungsten, and inert gas shielding are listed in table 16. In general, joint efficiency was reduced by a single repair from 100 to approximately 90 percent.

Characteristic data for LA91A fusion weldments are listed in table 17. Weld efficiencies near 100 percent can be obtained in LA91A. All weldments exhibit sufficient ductility at cryogenic temperatures to warrant use of LA91A in lightly loaded space structures.

Results from single repair welds in LA91A are shown in table 18. Joint efficiency was reduced from 100 to about 85 percent by a single repair weld.

TABLE 16.—*Joint Strengths of LA141 Repair Welds* [a]

Condition	Ultimate tensile strength, psi	Yield tensile strength, psi	Elongation in 2 in., %
Transverse butt weld pulled parallel to rolling direction	20 100	15 000	9. 5
Transverse butt weld pulled perpendicular to rolling direction	20 100	16 000	9

[a] NASA data.

TABLE 18.—*Joint Strengths of LA91A Repair Welds* [a]

Condition	Ultimate tensile strength, psi	Yield tensile strength, psi	Elongation in 2 in., %
Transverse butt weld pulled parallel to rolling direction	20 800	18 000	7. 5
Transverse butt weld pulled perpendicular to rolling direction	21 100	17 600	6. 5

[a] NASA data.

Experimental weldments in LAZ933A have been made at Battelle (ref. 3). These welds were made by the automatic, tungsten, inert gas (TIG) process on 4x6x0.063-inch-thick plates. Prior to welding, the plates were cleaned in a CrO_3–$NaNO_3$–H_2O solution. All welds were of the bead-on-plate type and traversed the long axis of the sheet. Direct-current straight polarity was used without filler wire. Additional welding conditions are as follows:

Head	Automatic-voltage-control type.
Electrode	Tungsten with 1% ThO_2 (1/8-inch diam.).
Shielding cup size	11/16-inch inside diam.

TABLE 17.—*Mechanical Properties of LA91A Magnesium-Lithium Alloy Weldments* [a]

Temperature, °F	Ultimate tensile strength, psi	Yield tensile strength, psi	Elongation in 2 in., %	Fracture location
75	23 700	21 200	6	Base metal
75	23 700	21 800	6	Base metal
75	23 400	21 400	6	Base metal
−320	30 400	25 700	7	Base metal
−320	30 200	----------	12	Base metal
−423	43 300	----------	6	Fusion zone
−423	38 100	----------	1	Fusion zone
−423	39 400	----------	3	Fusion zone

[a] Sheet thickness, 0.090 inch. TIG welding using EZ33A filler wire. NASA data.

Shielding gas..... Helium at 300 cu ft/hr flow rate.
Preheat..... None.
Welding current..... 45 A.
Arc voltage..... 12 V.
Travel speed..... 12 in./min.
Root shielding..... Helium at 10 cu ft/hr.

Plates were welded without incident. Radiographs of the four welds showed them to be free of cracks and porosity which was subsequently substantiated in metallographic examination. Testing for bend ductility indicated a minimum bend radius of ¼ inch at room temperature.

RESISTANCE WELDING

Magnesium-lithium alloys can be readily spot welded on equipment conventionally used for other magnesium alloys. However, as with all joining operations involving these alloys, extreme care must be exercised in preparing the surfaces to be welded. After cleaning, the alloys should be spot welded without delay. Because of chemical reactivity, spot welding of the alloys after coating has been recommended.

Available data for spot welds in bare LA141A joined to itself, to AZ61 and to AZ91 are shown in table 19. All spot welding used a standard production-type "Sciaky" press spot welder of 150 kva electrical capacity and equipped with "Dekatron" sequence controls. The LA141A sheet was 0.064 inch thick. In general, the mechanical properties of all spot welds exceed the requirements of military specifications.

TABLE 19.—*Weld Joint Strengths of LA141A Magnesium-Lithium Alloy at Room and Elevated Temperatures* [a]

Material combination	Test temperature, °F	Tension strength, lb	Shear strength, lb
LA141A+LA141A	70	236	749
LA141A+LA141A	150	352	630
LA141A+AZ61	70	277	984
LA141A+AZ61	150	283	806
LA141A+AZ91	70	264	894
LA141A+AZ91	150	298	813

[a] LMSC data.

TABLE 20.—*Effect of Surface Treatment on LA141A Spot Weldments* [a]

Surface treatment	Surface resistance	Tension shear, lb	Weld schedule
4% HNO_3 in ethanol	1 000	860	Standard.
4% HCl in ethanol	1 000	840	Standard.
10% HCl in ethanol	1 000	840	Standard.
$H_3PO_4NH_4OH$ in H_2O.	20 000	536	Standard.
50% CrO_3 in H_2O	80	592	Standard.
50% CrO_3 in H_2O	80	1 185	Increased heat.
Bare LA141A	--------	843	

[a] Convair data.

Table 20 shows the effect of various surface treatments on the strength of LA141A spot welds.

A 50 percent CrO_3-solution surface treatment significantly increases spot-weld strengths.

The effect of a stress-relief heat treatment on LA141A spot welds is shown in table 21. In general, delayed weld cracking of LA141A spot welds can be eliminated by a stress relief at 250° F for 24 hours.

TABLE 21.—*Effect of Time on Weld Cracking* [a]

Elapsed time after welding, days	Number of weld cracks [b] (no post-weld treatment), 12 samples
11	0
14	2 (17%)
16	3 (25%)
18	7 (58%)
21	9 (75%)
24	9 (75%)
28	11 (92%)
31	11 (92%)
35	12 (100%)
44	----------

[a] Convair data; chromate coating, LA141A spot welds.

[b] There were no weld cracks for welds aged 24 hours at 250° F (24 samples).

ELECTRON-BEAM WELDING

The limited data available indicating the properties of LA141A weldments made by electron-beam welding are listed in table 22.

TABLE 22.—*LA141A Electron-Beam Weldments* [a]

Material	Ultimate tensile strength, psi	Yield tensile strength, psi	Elongation in 2 in., %
LA141A	21 300	17 000	22
Weldment	21 000	16 400	22

[a] Ref. 11.

These data suggest that electron-beam welding yields joint strengths and ductilities equal to base-metal properties. Microscopy indicates no weld defects and reveals a very narrow heat-affected zone.

SOLDERING AND BRAZING

Soldering and brazing are not used extensively for commercial magnesium alloys. However, since brazing is of great importance in the aerospace industry, especially in guidance components, joining magnesium-lithium alloys by this process may be required.

Only experimental data are available. At Battelle (ref. 19), several attempts were made to torch-braze LA141 to itself, using a lap joint with AZ125XA filler metal. The base metal melted before the filler metal. Additional attempts were made to furnace-braze the alloy at 1100° and 1080° F using the same filler. Again, the base metal melted along with the filler metal.

These results indicate that additional research is needed to develop techniques for brazing magnesium-lithium alloys. Primarily, the work should emphasize new brazing filler alloys having melting ranges compatible with the magnesium-lithium alloys.

ADHESIVE BONDING

Magnesium-lithium alloys can be adhesive bonded using conventional materials and techniques. Good adhesion has been obtained on both uncoated and coated alloys. However, surface condition plays a significant role. Alloy LA141A has been adhesive bonded using several procedures.

Lockheed found the following method to be promising for bare LA141A:

(1) Clean the material by successively processing it first in trichloroethylene vapor and then in an alkaline solution
(2) Heat the cleaned plates in an air-circulating oven at 350°±20° F for one hour. Cool. Then wash them in tap water for 5 minutes at 100°±10° F
(3) Force-dry the material with air. Apply and cure a MIL–A–5090, Type I adhesive (Metalbond 406 or FM–1000)
(4) Testing has produced values in excess of 1000 psi lap shear tensile strength

Brooks and Perkins has recommended the use of surface coatings, such as Dow–17 or the HAE process. The following method is recommended:

(1) Scour surface with pumice until bright
(2) Rinse off, dry, heat to 450° F in an inert atmosphere
(3) Cool to room temperature in an inert atmosphere
(4) Submerge in cold water
(5) Fluoride-anodize at 5 A/ft^2 for 30 minutes
(6) Apply Hysol 4225, heat to 150° F to dry. Repeat as required
(7) Final bake at 375° F
(8) Bond with epoxy-type adhesive.

General Dynamics/Convair reports a single attempt to adhesive-bond LA141A. Specimens were cleaned in an HCl-ethanol solution and stored overnight in a vacuum desiccator. A 50/50 mixture of Epon 828 and Versamide 125 was applied to a 1-inch square area along with two 0.0019-inch wire spacers. The tension shear strength of the coupons 1 day after bonding averaged 1350 lb/in.^{2} While the tension shear strength of the bond approached that of the metal, the bond failed by adhesive failure, indicating that a primer would probably be necessary to produce satisfactory bonds.

By far, IBM has done the greatest amount of development for adhesive bonding of LA141A.

Some early IBM results are listed in table 23. These data show the feasibility of adhesive fabrication of lightweight structures.

More detailed IBM results are listed in table 24. These data indicate that optimum lap shear strength and tensile adhesion of Epon 934 and FM–1000 were not determined. Failure occurred in the fluoride anodized surface rather than in the adhesive. The results point out the need for additional development of low-temperature-cured polyurethane coatings and of surface anodizing treatment.

TABLE 23.—*Strength of Adhesive Bonding of LA141A* [a]

Adhesive	Type	Surface preparation	Primer or coating	Cure [b] temp, °F	Tensile-lap shear strength, psi
HT–424	Epoxy phenolic film	Fluoride-anodize		335–350	1600
HT–424	Epoxy phenolic film	Fluoride-anodize	Hysol 4225	335–350	1350
FM–1000	Modified epoxy film	Fluoride-anodize	Hysol 4225	315–350	2190
Pliobond HT–30	Nitrile phenolic liquid	HAE		300–350	1210
HT–424	Epoxy phenolic film	HAE	Hysol 4225	335–350	1070
Pliobond HT–30	Nitrile phenolic liquid	HAE	Hysol 4225	300–350	180
FM–1000	Modified epoxy film	Solvent clean	Hysol 4225	315–350	1960
FM–1000	Modified epoxy film	Solvent clean		315–350	1290

[a] IBM data.

[b] Cure time was 1 hour for all adhesives.

NOTE: HT–424 and FM–1000 are manufactured by the Bloomingdale Rubber Co.; Pliobond HT–30 is manufactured by the Goodyear Rubber Co.; and Hysol 4225 is manufactured by the Hysol Corp.

TABLE 24.—*Strength of Adhesive Bonding of LA141A with Epoxy Resins* [a]

Exposure before testing	Strength of bond		Exposure before testing	Strength of bond	
	Lap-shear, psi	Tensile, psi		Lap-shear, psi	Tensile, psi
Adhesive FM–1000 [b]			Adhesive Epon–934 [c]		
None	1400	5300	None	1200	3900
14 days in 20% salt spray per MIL–E–5272C	1400		None (tested at 250° F)	600	800
30 days room temperature control samples	1400		30 days humidity per MIL–E–5272C	760	1800
30 days in 60–40 methanol and water solution	1800		30 days in 60–40 methanol and water	910	
			48 hr in vacuum 10^{-6} torr, 150° F	1200	3200
			8 days in salt spray 20%, per MIL–E–5272C	900	2400

[a] IBM data. All failures occurred through the anodized layer.

[b] Epoxy 3-mil film cured 1 hour at 320° to 350° F in vacuum with a bond pressure of 45 to 50 psi. Adhesive supplied by Bloomingdale Rubber Co.

[c] A two-component epoxy resin; 4 mils of the liquid bond were cured 16 hours at room temperature followed by 2 hours at 150° F. Adhesive supplied by Shell Chemical Co.

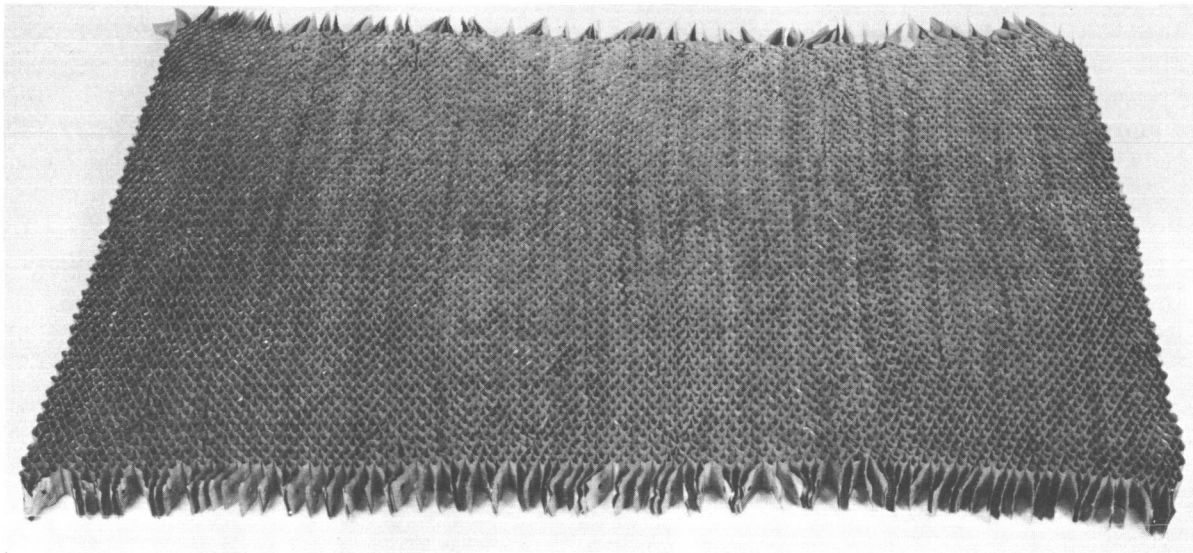

FIGURE 23.—Expanded magnesium-lithium alloy honeycomb core (⅞ inch thick by 17½ inches wide by 28 inches long).

Interest at NASA to develop magnesium-lithium alloy honeycomb has initiated study of adhesive bonding of LAZ933A. Currently, Battelle (ref. 4) is fabricating experimental quantities of core material for evaluation at temperatures between 180° and −423° F. Figure 23 shows an expanded LAZ933A honeycomb core. The structure was fabricated using the Bloomingdale FM–1000 adhesive with no coating on the foil which ranged in thickness from 0.0016 to 0.0017 inch.

MECHANICAL FASTENING

Magnesium-lithium alloys can be mechanically fastened to themselves or to other magnesium alloys. Limited data for pinned and riveted joints in LA141A are listed in tables 25 and 26.

Humidity tests of riveted joints showed very little difference between unprotected or protected LA141A or AZ31B to resist 100 percent relative humidity at 100° F for 100 hours. A 48-hour, 5-percent salt-spray test showed the LA141A sheet to be comparable to AZ31B or HM21A magnesium-alloy sheet in resistance to oxidation. The 5056 aluminum-alloy rivets (table 26) were found to be compatible with the LA141A sheet whereas the 6071 aluminum-alloy rivets were not suitable.

TABLE 25.—*Average Bearing Strength of LA141A Lapped Sheets Pinned Together Using a 2D Edge Distance*

Temperature, °F	Sheet thickness, in.	Pin diameter, in.	Transverse strength, psi		Longitudinal strength, psi	
			Bearing yield	Bearing ultimate	Bearing yield	Bearing ultimate
Room	0. 042	0. 250	31 000	45 000	30 000	46 000
Room	. 082	. 250	34 000	47 000	33 000	47 000
150	. 042	. 250	24 000	30 000	26 000	31 000
150	. 082	. 250	26 000	30 000	25 000	31 000

TABLE 26.—*Average Single Shear Joint Test of LA141A Sheet Riveted Together with 5/32-Inch Rivets of 5056 Aluminum Alloy* [a]

Temperature, °F	Sheet thickness, in.	Rivet head	Shear strength, lb			
			Transverse		Longitudinal	
			Yield	Ultimate	Yield	Ultimate
Room	0.040	Brazier	260	301	277	314
150			200	216	207	216
Room	.080	Brazier	540	661	528	642
150			405	448	408	445
Room	.080	Flush	369	580	382	556
150			321	390	297	369

[a] IBM data.

CHAPTER 7

Corrosion Resistance, Cleaning, and Finishing

The corrosion resistance of magnesium-lithium alloys is surprisingly good considering that they contain a relatively high percentage of a metal as active as lithium. For all practical purposes, the corrosion resistance of these alloys is similar to that for commercial magnesium alloys (ref. 1). In general, if other magnesium alloys need protection, magnesium-lithium alloys would also need protection in the same applications. To date, no aerospace hardware has been seriously affected by the corrosion susceptibility of magnesium-lithium alloys.

CORROSION RESISTANCE

The limited data available indicating the corrosion behavior of LA141A and LAZ933A are indicated in table 27. In general, preliminary corrosion studies in humid, salt-spray, and marine environments indicate a corrosion resistance comparable to that of the magnesium-thorium alloys (ref. 9). Fluoride-anodized and oiled samples of LA141A have passed several days of salt-spray exposure. However, to date no coating has been developed for the magnesium-lithium alloys that will permit passing the stringent requirements of MIL Specification E–5272. This is a very severe test, calling for 240 hours of cyclic exposure in 100 percent humidity at 165° F.

CLEANING

Magnesium-lithium alloys react readily with atmospheric gases. As a consequence, the alloys require extreme care in surface preparation, especially for subsequent operations, such as fusion and resistance welding, adhesive bonding or coating.

Numerous mechanical and chemical methods have been used to clean magnesium-lithium alloys. Stainless-steel or aluminum-wire brushes should be used. Aluminum wool and aluminum-oxide paper have also given good results. Regular steel wool and brushes as well as emery cloth should not be used. Because of the extreme oxidation rates of these alloys, the time interval between cleaning and subsequent joining should not exceed 30 minutes.

Most chemical cleaning methods use a solution originally developed for conventional magnesium alloys. General Dynamics/Convair found that the chromate coating process (described in Appendix C) gave satisfactory re-

TABLE 27.—*Resistance of Magnesium-Lithium Alloys to Corrosion in 100 Percent Humidity at 95° F* [a]

Alloy	Condition	No. of specimens tested	Corrosion rate, mdd [b]	Duration of test, days
LA141A	Abraded	2	15.2	16
	Uncoated	Not available	10.0	60
	Anodized	Not available	1.6	60
LA91A	Uncoated	Not available	9.0	60
	Anodized	Not available	1.7	60
LAZ933A	Abraded	8	15.4	15
	Unabraded	4	11.4	15

[a] Battelle data.
[b] Mg/sq decimeter/day.

sults on LA141A. This coating, although yellow-gray with a tendency to be blotchy and streaked, seemed to produce parts that were uniformly weldable. Also, General Dynamics/Convair has used an HCl cleaning solution for preparing surfaces for adhesive bonding. A description of this descaling process is included in Appendix C. This procedure produced bright surfaces that remained bright for considerable time.

Battelle Memorial Inst. and Lockheed have successfully used the Dow–21 process for cleaning LA141A and LAZ933A. This ferric nitrate bright pickle process is outlined in Appendix C.

After careful surface preparation, procedures for corrosion protection can be initiated.

FINISHING

A number of anodic and conversion coating treatments have been successfully used for the corrosion protection of magnesium-lithium alloys. These include Dow–17, HAE, and fluoride anodic processes. Specific conditions for applying these coatings are given in Appendix D. Conventional paint systems may be applied over the Dow–17, HAE, or fluoride coatings. Several commercial paint systems are available for successful use on these alloys, one of which is shown in Appendix D.

Various specifications cover coatings which have been shown to be effective on magnesium-lithium alloys. These are:

Coating Specifications

Vinyl Coatings:

(1) Wash primer (MIL–P–15926) clear or gray vinyl coatings (Navy)
(2) MIL–E–13515 covers all colors and olive drab (Air Force)
(3) MIL–L–14486 (Ordnance)

Epoxy and Wash Primer:

(1) MIL–C–15328
(2) MIL–P–27316

An adaptation of the British Aroldite 985E painting process has been used by IBM for painting magnesium-lithium alloys. This is given in Appendix D. Hysol 4225 resin and Hysol 5126 solvent are specified, but other similar epoxy formulations would probably work as well.

In addition to finishing, metallic coatings can be applied to magnesium-lithium alloys. These are discussed in the section that follows.

METALLIC COATINGS

There are three accepted methods of applying metallic coatings to commercial magnesium alloys: (1) immersion zinc plating, (2) electroless (immersion) nickel plating, (3) direct electroplating of nickel. The first two methods were found to be far more effective than the third. In each case, other metals that can be electroplated can be deposited by standard methods over the initial layer of zinc or nickel.

LA141A has been effectively plated using commercially available processes. However, as in preparing magnesium-lithium alloys for surface treatments, such as welding, coating, and adhesive bonding, extreme care must be taken to insure a fresh uncontaminated surface.

Immersion Zinc Plating

An immersion zinc plating method developed by IBM is described in Appendix E.

Electroless nickel plating can be applied directly to magnesium-lithium alloy surfaces by using the chemical-etch method of pretreatment. This method is outlined in Appendix E.

Electroless Nickel Plating

Electroless nickel is deposited on magnesium surfaces by continuous chemical reduction without applied current (ref. 20). The solution from which the nickel is deposited contains nickel acid fluoride, sodium hypophosphite, and a pH buffering or complexing compound. This method of plating is said to be satisfactory for magnesium-lithium alloys (H. K. DeLong, Dow Metal Products Co.), but no published data are available.

The electroless nickel coating is resistant to continuous heating at 700° F and to thermal shock if it is stress-relieved for 2 hours at 350° F. The fatigue strength of commercial mag-

nesium is said to be improved by as much as 60 percent by the nickel coating (ref. 20).

The chemical-etch method of pretreatment which enables the electroless nickel plate to be applied directly to the magnesium-lithium alloy surfaces is described in Appendix E.

This method involves etching by an aqueous bath containing either chromic acid or bichromate and nitric acid. A very fine etch is produced with undercut pits which provides an excellent base for adherent metal coatings. Since the magnesium surfaces are etched, the final nickel surface will not be as smooth as those using the zinc-immersion method. Because of the severe action of this chemical etch, usually no other pickling is necessary to clean the surface before etching. The etching is a two-step process. After the chromic-acid dip and water rinse, the work is dipped into an aqueous hydrofluoric acid solution. This HF dip removes all trace of chromate and replaces the chromate film with a fluoride film. The operating conditions of the chemical etch are given in Appendix E. Longer treatment times produce better adhesion, but the surface roughness is also increased.

Immediately after rinsing, the work is transferred to the electroless nickel-plating bath (see Appendix E). After the nickel has been applied to the alloy surface, the coating should be annealed for 2 hours at 350° F, particularly if the coating is to be subsequently exposed to high temperatures, such as in soldering. Finally, the corrosion resistance of the coating can be improved by a passivating treatment in a chromate solution. This treatment should be done after soldering, adhesive bonding, or other such operations.

Direct Nickel Electroplating

Nickel can be electroplated directly onto magnesium alloys from a nickel acid fluoride solution. This plating method can also be used over the zinc-immersion-plus-copper-strike coating to assure nickel coverage in deeply recessed areas. If the zinc-immersion method of preparation is not used, a chemical-etch pretreatment must be used.

A nickel coating may be electrodeposited from the bath described in Appendix E. The nickel coatings are semibright and relatively smooth. A thin strike of this nickel plate approximately 0.0001 to 0.0003 inch thick is applied. Bright nickel can be used, other electroplates can be applied, or the nickel coating can be applied from the same bath in thicker layers for wear resistance.

The quality of the nickel coating electrodeposited directly onto the magnesium metal is not as good as that produced over the zinc-immersion coating or by the electroless nickel method. It has not been demonstrated that this method is applicable to magnesium-lithium alloys.

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CHAPTER 8

Casting and Ingot Production

Magnesium-lithium alloys can be melted and cast by the conventional flux methods used for other magnesium alloys. However, lithium and, to a lesser extent, magnesium react readily with oxygen and nitrogen in the temperature range of 1200° to 1400° F required for melting. Three methods have been developed which protect the molten alloy during melting and casting.

The simplest and most economical protection is given by a flux cover, usually molten, which can be maintained on the exposed surface of the melt and which can be readily removed prior to casting. The technique, developed by Battelle for producing small ingots of magnesium-lithium alloys (refs. 2 and 21), is as follows.

(1) Premelt enough 3:1 LiCl:LiF flux in a steel crucible to give a total melt consisting of 25 to 30 percent flux, the rest alloy.
(2) Charge the required amount of solid magnesium to the molten flux. The magnesium, being heavier, sinks and is protected by the flux cover at this stage.
(3) Charge the required amount of heavier alloying additions; e.g., aluminum, zinc, silver.
(4) Charge the required amount of lithium by submerging and stirring it into the melt. After the lithium addition, the alloy becomes lighter than the flux, which then sinks to the bottom of the crucible.
(5) Stir the mixture vigorously and allow a 15-minute settling period. During this period, a thin layer of flux on top of the molten alloy protects it from the atmosphere, while the remainder of the flux settles to the bottom of the crucible. Lithium bromide may be added to the flux, after alloy additions are stirred in, in order to increase the flux density to improve separation.
(6) Remove the flux film, which becomes somewhat viscous during the settling period, and pour by decanting the melt from above the bottom flux layer.

A modification of this flux method was used by Dow Chemical Co., Madison, Ill., to handle 4000-pound heats (ref. 1). Currently, Battelle is developing a flux method to refine and recover commercial magnesium-lithium scrap. Because of the dangers involved, open-crucible flux melting is not currently recommended for commercial production of large heats.

A second method, currently used by Brooks and Perkins Co. to produce commercial magnesium-lithium alloys, utilizes an inert-gas cover to protect the molten metal. This method is simple and similar to the flux process and requires only an argon cover to protect the molten metal.

As a consequence of the difficulties associated with producing magnesium-lithium alloys by the flux and inert-gas methods, Battelle is currently investigating the development of a vacuum-induction melting method. This study involves use of a conventional commercial vacuum-melting furnace equipped for induction melting under remote control. In earlier work for the Army Ballistic Missile Agency (ABMA), now the Marshall Space Flight Center, NASA, several ingots weighing less than 100 pounds were poured in this furnace. No flux was used. The system was completely evacuated before melting and a 30-μ pressure of argon was bled back into the system to minimize vaporization.

The development of a vacuum-induction method will lead to the production of good-quality ingots and a new commercial method for producing the alloys.

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CHAPTER 9

Fabrication

Magnesium-lithium alloys, in contrast to other established magnesium alloys, are easily fabricated and formed, even at room temperature. Primarily, the excellent forming characteristics of these alloys are associated with their body-centered cubic crystal structure. Conventional magnesium alloys exhibit a hexagonal close-packed structure and require special forming techniques.

Magnesium-lithium alloys are readily produced by almost all methods of primary fabrication. To date, the alloys have found application primarily as sheet and plate. Maximum sizes for LA141A are given in table 28. Thinner (0.003 to 0.020 inch) and thicker (2.0 to 6.0 inches) gages have been produced. Extrusions, having cross-sections circumscribed by a 7-inch diameter circle, and forgings are available in LA141A and other shapes and other alloys are available from Brooks and Perkins on special order.

TABLE 28.—*Maximum Sheet and Plate Sizes of LA141A*

Thickness, in.	Width, in.	Length, in.
0.020–0.040	24	144
0.040–0.050	36	----------
0.050–2.0	48	24

Forming

As with primary fabrication, secondary forming of magnesium-lithium alloys is readily accomplished. For LA141A, the bend radius in the longitudinal direction is 1 T [1] at room temperature. Transverse to the rolling direction, LA141A bends with a radius of 3 to 3½ T. Above 150° F, the alloy may be readily bent through a 1-T radius. Deep-drawing, impact-extruding, spinning, and hammer-forming require temperatures up to 500° F, the needed temperature depending on the severity of forming (ref. 8).

Recently, difficulties in forming LA141A have been encountered. Cracking, orange-peel structure, and delamination have been observed. These defects are possibly associated with the manufacturing process and are not inherent in the alloy.

Machining

Magnesium-lithium alloys are easily machined, cut, sawed, or chemically milled. In machinability, they have been compared to other magnesium-base alloys and aluminum. The same special precautions used in magnesium machining must be observed.

Where a machining coolant or lubricant is desired, a mineral oil (nonwater-soluble) is recommended. For cutting or sawing, mineral oil or paraffin may be used.

[1] One times the thickness.

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APPENDIX A

Summary of Magnesium-Lithium Alloy Development

The development of magnesium-lithium alloys began in 1942 at Battelle Memorial Inst. under the sponsorship of Mathieson Chemical Corp. The object of this early work was the development of lightweight magnesium-lithium alloys exhibiting higher strengths, better formability, and less directionality than conventional magnesium alloys.

In 1945, when magnesium-lithium alloys were found to be of interest as a potential structural material, the Bureau of Aeronautics, Navy Dept. entered into a cooperative agreement with Mathieson for the sponsorship of further investigational work. Under Navy sponsorship, development of magnesium-lithium alloys continued at Battelle until 1957. It was during this period that the application of the alloys in fragment armor was developed. During the late 1940's and 1950's, research on alloy development was also being sponsored by the Army at Dow Metal Products Co.

During these years, the effects of practically all of the metallic elements on the properties of the magnesium-lithium alloys were investigated. The order of solid solubility of the elements at room or slightly elevated temperatures was found to be as follows:

Most soluble elements

Ag	Cd	Al
	Hg	In
	Zn	Tl

Slightly soluble elements

Ni	Cu	Ca	Si	Sb
Co		Sr	Ge	Bi
		Ba	Sn	
		Ce	Pb	

Relatively insoluble elements

K	Be	Cr	Ti	V	Mn
	B	Mo	Zr	Nb	
		W	Th		
		U	Fe		

The elements which most effectively increased the mechanical strength of the magnesium-lithium base were aluminum, zinc, silver, and cadmium. Aluminum was found to be the most effective strengthener.

In the course of the above work, a number of promising alloys were extensively evaluated. Alloys containing 10 to 20 percent of one or more of the elements aluminum, zinc, cadmium, or silver were found to respond vigorously to heat treatment. Tensile strengths were obtained between 50 000 and 65 000 psi. Examples of such alloys are Mg–12Li–15Cd–5Ag, Mg–14Li–10Al, and Mg–12Li–20Zn. The mechanical properties of two of the more promising high-strength alloys developed are presented in table A–1. Unfortunately, the strength of these alloys decreases at only moderately high temperatures. Consequently, the alloys were not recommended for use in a heat-treated, high-strength condition. This instability, or tendency to lose strength at slightly elevated temperatures, has been studied by many investigators but has not yet been overcome.

As a result of the early Battelle work, magnesium-lithium alloys containing around 13 to 14 percent lithium plus 1 to about 6 percent aluminum were recommended for their excellent armor characteristics and a Navy specification was issued. These alloys also exhibited good formability at moderately high strength levels.

TABLE A–1.—*Mechanical Properties of Two Alloys*

Alloy	Ultimate tensile strength, psi	Yield tensile strength, psi	Elongation, %
Mg–13Li–6Al	40 800	37 000	10
Mg–12Li–15Cd–5Ag	46 000	43 000	8

In 1957 the Ordnance Tank Automotive Command contracted to Dow Chemical Co. and Food Machinery Corp. for the fabrication of an experimental magnesium-lithium hull for the M113 armored personnel carrier. The Mg–13Li–6Al (LA136) was first selected for this application but was later abandoned in favor of the Mg–14Li–2Al (LA142) alloy. Edge cracking during rolling and weld cracking were the major difficulties encountered with LA136, owing to the high aluminum content. Figure A–1 shows the prototype body of the M113 vehicle made from LA142.

Although this prototype vehicle successfully passed road testing, the magnesium-lithium hull was not used in the production model. Primarily, costs, lack of resistance to long-term corrosion, and poor resistance to AP projectiles were the determining factors.

Also in 1957, the Research Projects Office of the Army Ballistic Missile Agency, Redstone Arsenal (now the Marshall Space Flight Center), initiated at Battelle the development of magnesium-lithium alloys for possible aerospace activities. This work was continued until May 1964 under the supervision of the Propulsion and Vehicle Engineering Laboratory.

Essentially, the research comprised the screening of magnesium-lithium alloys made in previous years and the selection and evaluation of the compositions that would have the

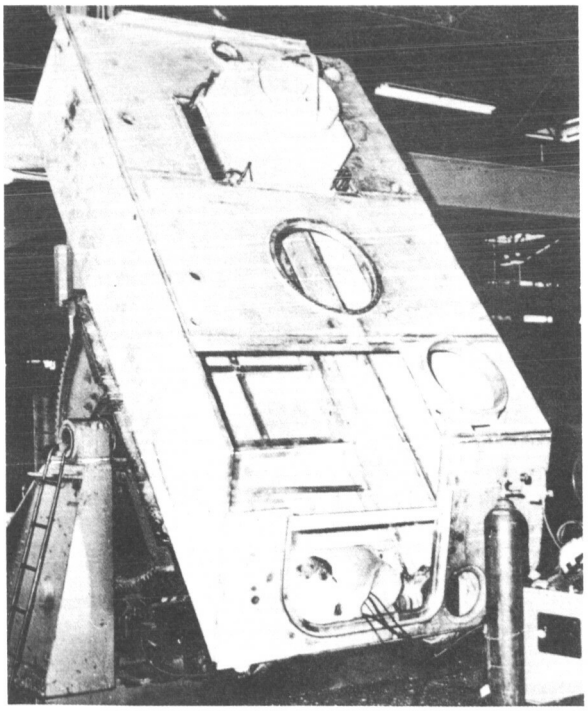

FIGURE A–1.—Prototype body of the M113 armored vehicle made from a magnesium-lithium alloy.

greatest potential use in aerospace applications. The three alloys selected had the following nominal composition: Mg–14Li–1Al (LA141A), Mg–9Li–1Al (LA91A), and Mg–9Li–3Al–3Zn (LAZ933A). The report on the Battelle research recommended the LA141A alloy as the composition having the greatest immediate potential. Since 1960, aerospace companies, notably the Lockheed Missiles and Space Co. and the Federal Systems Division of IBM Corp., have made good use of the information presented in the NASA report and have generated much more data on the properties and uses of the LA141A alloy. More recently, the Convair Div. of General Dynamics has initiated extensive evaluation of the same alloy.

In addition to the alloy development work at Battelle, the Pitman-Dunn Laboratory at Frankford Arsenal has maintained an active program on magnesium-lithium alloys since the early 1950's. About 1961, efforts at the laboratory culminated in the development of two new alloy compositions. The alloys have the following nominal compositions: Mg–14Li–0.5Si and Mg–14Li–5Zn–3Ag–2Si. These alloys have been developed to the point where small-scale evaluation tests are being conducted.

Since 1964, the American Machine and Foundry Co., Alexandria, Va., has been conducting research on magnesium-lithium alloys under the supervision of the Marshall Space Flight Center. The purpose of this program has been to develop lightweight, wrought magnesium alloys for applications requiring high strength, high ductility, and low notch sensitivity at cryogenic temperatures. Specifically, the ultimate goal is to develop an alloy with a tensile strength of 45 000 psi, a yield strength of 35 000 psi, and a 20 percent elongation at temperatures from −423° F to room temperature; contractual goals call for these minimum properties over the entire range, except that at the low limit the elongation may decrease to 15 percent. Weldability is also a requirement.

Currently three alloy compositions have been selected for pilot plant production. Their nominal compositions are: Mg–1Zr–3Th–7Li–6Zn–5Cd–6Ag, Mg–2Th–7Li–9Zn, Mg–3Th–9Li–2Zn–1Mn–4Al–4Ag. Thus far in the testing program, two of the alloys chosen for scale-up are close to meeting the ambient-temperature contractual goals.

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APPENDIX B

Aerospace Material Specifications

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AEROSPACE
MATERIAL SPECIFICATIONS

SOCIETY OF AUTOMOTIVE ENGINEERS, Inc. 485 Lexington Ave., New York 17, N.Y.

AMS 4386

Issued 6-30-64
Revised

MAGNESIUM ALLOY SHEET AND PLATE
14.0Li - 1.25Al (LA 141A-T7)
Stabilized

1. ACKNOWLEDGMENT: A vendor shall mention this specification number in all quotations and when acknowledging purchase orders.

2. APPLICATION: Primarily for components requiring weldability and good formability with low density for low temperature and low stress usage.

3. COMPOSITION:

	min	max
Lithium	13.0	15.0
Aluminum	1.00	1.50
Manganese	--	0.15
Silicon	--	0.10
Copper	--	0.04
Nickel	--	0.005
Iron	--	0.005
Sodium	--	0.005
Total Other Impurities	--	0.30
Magnesium	remainder	

4. CONDITION: Stabilized at 350 F ± 25 (176.7 C ± 14) for 3 - 6 hr and acid pickled.

5. TECHNICAL REQUIREMENTS: When ASTM methods are specified for determining conformance to the following requirements, tests shall be conducted in accordance with the issue of the ASTM method listed in the latest issue of AMS 2350.

5.1 Tensile Properties: Test specimens shall conform to ASTM E8 and shall be taken parallel to the direction of rolling. Sheet type specimens shall be used for material less than 0.5 in. thick and 0.75 in. and over in width. Round specimens shall be used for material 0.5 in. and over in thickness and 0.75 in. and over in width. Material under 0.75 in. wide and under 0.5 in. thick may be tested in either full section or by use of round specimens; for such sizes, elongation requirements apply only when round specimens are used. Testing shall be conducted at a rate of 0.003 - 0.007 in. per in. per min. up to the yield strength and not more than 0.5 in. per in. per min. above the yield strength.

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AMS 4386

Nominal Thickness Inches	Tensile Strength psi, min	Yield Strength at 0.2% Offset or at Extension Indicated (E = 6,000,000) psi, min	Extension Under Load in. in 2 in.	Elongation % in 2 in. or 4D min
0.010 to 0.090, incl	19,000	15,000	0.0090	10
Over 0.090 to 0.250, incl	19,000	14,000	0.0087	10
Over 0.250 to 2.000, incl	18,000	13,000	0.0083	10

5.1.1 When a dispute occurs between purchaser and vendor over the yield strength value, yield strength determined by the offset method shall apply.

5.1.2 If sizes other than those shown are ordered, tensile property requirements shall be as agreed upon by purchaser and vendor.

6. QUALITY: Material shall be uniform in quality and condition, clean, sound, and free from foreign materials and from internal and external imperfections detrimental to fabrication or to performance of parts.

7. TOLERANCES: Unless otherwise specified, tolerances shall conform to all applicable requirements of latest issue of AMS 2202, except that flatness tolerances shall be as follows:

7.1 Longitudinal Flatness:

Nominal Thickness Inches	Tolerance, Inch (See Note 1)
0.250 - 3.000, incl	3/16 in any 6 ft (See Note 2)
Over 3.000 - 6.000, incl	1/8 in any 6 ft or less

7.2 Transverse Flatness:

Nominal Thickness Inches (See Note 3)	Tolerance, Inch (See Note 1) Width Ranges, Feet: 2 and under	Over 2 to 4, incl	Over 4 to 6, incl
0.250 - 0.625, excl	Only short	5/16	3/8
0.625 - 1.500, incl	cycle flatness	3/16	5/16
Over 1.500 - 3.000, incl	tolerance	3/16	3/16
Over 3.000 - 6.000, incl	applies	1/8	1/8

7.3 Short Cycle Flatness (See Note 4):

Nominal Thickness Inches	Tolerance, Inch (See Note 5)
0.250 - 0.625, incl	0.100
Over 0.625 - 6.000, incl	0.075

Note 1. As measured with the plate resting on a flat surface, concave side upward, using a straight edge and a feeler gauge, dial gauge, or scale.

Note 2. For lengths under 6 ft, the tolerance is 1/8 inch.

Note 3. The term "excl" is used to apply only to the higher figure of the specified range.

Note 4. Short cycle flatness is the flatness over any 2-ft span in any direction.

Note 5. As measured with the plate resting on a flat surface, and by use of a frame with rollers mounted on 2-ft centers and a depth gauge in the center.

8. REPORTS:

8.1 Unless otherwise specified, the vendor of the product shall furnish with each shipment three copies of a report stating that the product conforms to the chemical composition and technical requirements of this specification. This report shall include the purchase order number, material specification number, thickness, size, and quantity.

8.2 Unless otherwise specified, the vendor of finished or semi-finished parts shall furnish with each shipment three copies of a report showing the purchase order number, material specification number, contractor or other direct supplier of material, part number, and quantity. When material for making parts is produced or purchased by the parts vendor, that vendor shall inspect each lot of material to determine conformance to the requirements of this specification, and shall include in the report a statement that the material conforms, or shall include copies of laboratory reports showing the results of tests to determine conformance

9. IDENTIFICATION: Unless otherwise specified, each sheet and plate shall be marked on one face, in the respective location indicated below. Symbols shall be applied using a suitable marking fluid and shall be sufficiently stable to withstand normal handling.

9.1 Flat Sheet and Plate 0.375 In. and Under Thick, 6 - 60 In., Incl, Wide, and 36 - 200 In., Incl, Long: Shall be marked in rows of symbols not less than 3/8 in. in height and recurring at intervals not greater than 3 feet. Rows shall run parallel to the direction of rolling of the piece and shall be spaced approximately 6 in. on centers across the width. Every third row shall show the manufacturer's identification and nominal thickness in inches. The other rows shall show the alloy number and temper, or AMS 4386, and shall be staggered.

9.2 Flat Sheet and Plate Over 0.375 In. Thick, or Over 60 In. Wide, or Over 200 In. Long: Shall be marked as in 9.1 above or, at vendor's discretion, shall be marked in one or two rows of symbols not less than 3/8 in. in height and running around the perimeter of the piece. If one row is used, it shall show the alloy number and temper, or AMS 4386, manufacturer's identification and nominal thickness in inches. If two rows are used, one row shall show the alloy number and temper, or AMS 4386; the second row shall show the manufacturer's identification and nominal thickness in inches.

9.2.1 If perimetral marking is applied to the full piece as produced but partial sheets or plates are supplied, an arrow shall also be applied near one corner indicating the direction of rolling.

9.3 Circles: Shall be marked with the alloy number and temper, or AMS 4386, manufacturer's identification, and nominal thickness in inches, when the circle diameter is 24 in. or more. Circles less than 24 in. in diameter shall be identified as agreed upon by purchaser and vendor.

10. PROTECTIVE TREATMENT: Unless otherwise specified, material shall be oiled with a light corrosion-inhibiting oil. Material shall be protected during shipment and storage by interleaving with suitable paper sheets.

11. REJECTIONS: Material not conforming to this specification or to authorized modifications will be subject to rejection.

APPENDIX C

Cleaning Procedures

Chromate Coating Process for LA141A

(1) Immerse coupons for 5 minutes in a 50 percent (by weight) solution of chromic oxide (CrO_3) in water
(2) Rinse twice in water
(3) Rinse in denatured ethanol
(4) Ultrasonically rinse in denatured ethanol
(5) Allow to air-dry.

Descaling Procedure for Metallic Finish

(1) Immerse coupons for 4 to 6 minutes in a solution of 3 percent (by volume) of reagent-grade HCl (36 percent) in denatured ethanol
(2) Rinse twice in denatured ethanol
(3) Ultrasonically rinse for 30 seconds in denatured ethanol
(4) Allow coupons to air-dry.

Dow-21 Ferric Nitrate Bright Pickle Process

Uses: Protection during storage, as a paint base, general cleanup, and pickle. Prevents tarnish indoors for 6 months.
Type of Bath: Immersion or spray
Bath Composition:

Step I		Step II	
CrO_3	24 oz	Sodium metasilicate	5% (by weight)
$Fe(NO_3)_3 \cdot 9H_2O$	5⅓ oz	Water	Balance
KF	0.47 oz	(Use step II only if part is stained)	
Water	To make 1 gal		

Operating Conditions:

Step I		Step II	
Temperature	60° to 100° F	Temperature	160° to 180° F
Time	Short dip	Time	½ to 1 min

Dimensional Change: 0.0015 in./surface/min
Pretreatments: Vapor degreased, alkaline cleaned
Posttreatments: Rinse in cold running water and in hot water to dry
Remarks: This treatment accentuates such defects as flow marks and segregation on cast surfaces. The concentration of KF is critical.

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APPENDIX D

Finishing Procedures

Dow-17 Conversion Coating

Uses: For corrosion protection, as paint base, reducing galvanic corrosion, decoration, and abrasion resistance

Type of Bath: Anodic ac

Bath Composition:

NH_4HF_2	32 oz
$Na_2Cr_2O_7 \cdot 2H_2O$	13.3 oz
H_3PO_4	11.5 fl oz
Water	To make 1 gal

Operating Conditions:	*Thin coat*	*Thick coat MIL-M-45202-ORD*
Temperature	160° to 180° F	160° to 180° F
Time	2.5 to 41 min	11 to 24 min
Current density	5 to 50 A/sq ft	5 to 50 A/sq ft
Voltage	60 to 110 dc	65 to 90 ac
Appearance of Coating	Light gray or green	Dark green
Thickness of Coating	0.0003 in.	0.0015 in.
Dimensional Change	0.0002 in.	0.001 in.
Pretreatment	Alkaline cleaner	Alkaline cleaner
Posttreatments	Sodium tetrasilicate seal or paint	Dichromate-bifluoride sealing

Tank Materials: Steel, synthetic rubber, vinyl plastic

HAE Process, Conversion Coating MIL-C-13335

Uses: For wear resistance, as paint base, corrosion resistance, and high-temperature resistance

Protective Value:

Corrosion resistance	Good
Abrasion resistance	Excellent; harder than steel of Rockwell C 65 (Moh hardness of 7 to 8)
Dielectric strength	500 to 600 V, 1.5-mil thickness

Type of Bath: Anodic

Bath Composition:

KF	35 g/liter
K_2MnO_4 in water	22 g/liter
KOH	120 g/liter
Na_3PO_4	35 g/liter
$Al(OH)_3$ or Al metal	30 g/liter
Water	To make 1 liter

Operating Conditions:

Temperature	Room (below 85° F)
Time	60 to 90 min
Current density	18 A/sq ft
Voltage (initial)	About 40 ac
(terminating)	80 to 85 ac

Appearance of Coating: Dark brown, brittle

Thickness of Coating: 0.001 inch

Dimensional Change: 0.0008-inch increase
Forms and Alloys Used on: All alloys, preferably thick sections because of brittleness of coating
Tank Material: Steel, glass, rubber
Rack Material: Mg alloy, masked at liquid-vapor interface
Posttreatment: Dichromate-bifluoride sealing
Remarks: Can be applied over chrome pickled surface. Arcing between parts must be prevented. Tanks must be kept cool. Units should be assembled before coating is applied.

Fluoride Anodize Treatment

Uses: For pretreatment, painting, and corrosion resistance
Type of Bath: Anodic
Bath Composition:

NH_4HF_2	30±5% (by weight)
Water	Balance

Operating Conditions:

Temperature	86° F (maximum)
Time	30 min
Current density	About 5 A/sq ft
Voltage	Up to 110 to 120 V
Immersion depth	At least 9 in.
Anode and cathode	Equal area

Rack material: AZ31B magnesium alloy
Pretreatments: Caustic potash cleaning
Remarks: Workpiece must be entirely magnesium with no inserts.

Commercial Paint System

(1) Apply Dow-17 (60 volts)
(2) Apply one coat (MIL–C–15328 of wash primer (with 20 percent of the H_3PO_4 replaced by isopropanol)
(3) Apply three coats of Truscon Chemfast epoxy enamel (total paint thickness about 0.003 inch)

Adaptation of British Aroldite 985E Painting Process

(1) Mechanically clean
(2) Vapor degrease
(3) Alkaline phosphate
(4) Heat in circulating air 1 hour at 420° F to oxidize lithium
(5) Rinse in running water 100° F for 5 minutes
(6) Fluoride anodize
(7) Heat to 300° F in circulating air to dry
(8) Cool to 130° F in air
(9) Dip-coat with a mixture of equal parts of Hysol 4225 and Hysol 5126 or spray-coat with a mixture of 55 percent Hysol 4225 and 45 percent Hysol 5126
(10) Air-dry at room temperature 30 minutes to cure
(11) Repeat steps 7, 8, 9, and 10 to give 1.5- to 2-mil paint thickness
(12) Bake in an air-circulating furnace at 365° F for 1 hour for final cure

APPENDIX E

Metallic Coating Procedures

IBM Plating Technique for LA141A

(1) Vapor degrease
(2) Electrolytic alkaline clean in 8 oz/gal Oakite No. 62 at 180°±10° F for 5 minutes utilizing a periodic reversed current of 5 seconds cathodic and 40 seconds anodic at a potential of 6 volts
(3) Cold water rinse
(4) Pickle in 5 percent HNO_3 to remove heavy oxidation formed during alkaline cleaning
(5) Cold water rinse
(6) Zincate, in a solution controlled and operated as follows:
  4 oz/gal zinc sulfate monohydrate
  16 oz/gal sodium pyrophosphate anhydrous
  0.67 oz/gal sodium fluoride
  0.67 oz/gal sodium carbonate
  10 g/liter sodium acetate
  175° to 185° F
  8.0 pH
  Immersion time: 3 to 10 minutes
  Agitation: light
(7) Cold water rinse
(8) Copper strike in a copper cyanide solution controlled and operated as follows:
  5.5 oz/gal copper cyanide
  9.0 oz/gal potassium cyanide
  4.0 oz/gal potassium fluoride
  1.0 oz/gal free cyanide
  130° to 140° F temperature
  9.6 to 10.4 pH (colorimetric)
  Current density: 5 to 10 A/sq ft
  Time: 6 minutes approximately
(9) Cold water rinse
(10) Hot water rinse and dry
(11) Bake [1] at 300°±10° F for 1 hour in a circulating air oven
(12) Cool to room temperature and immerse for 10 seconds in copper strike, no current on. Plate 1 minute at 5 A/sq ft
(13) Cold water rinse
(14) Addition plating as required

[1] The baking operation is for the purpose of alloying the copper, zinc, and magnesium alloy.

Pretreatment for Electroless Nickel Plating

Type of Treatment or Coating: Cleaning and activating pickle
Process Name: Chemical etch treatment
Use: Pretreatment for electroless nickel plating
Type of Bath: Immersion
Bath Composition:

Step I		Step II	
CrO_3	120 g/liter	HF (70%)	220 ml/liter
HNO_3(70%)	110 ml/liter	Water	To make 1 liter
Water	To make 1 liter		

OR

CrO_3	60 g/liter
HNO_3(70%)	90 ml/liter
Water	To make 1 liter

OR

HF (70%)	54 ml/liter
Water	To make 1 liter

Operating Conditions:

STEP I

Temperature	Room
Time	20 sec to 2 min

STEP II

Temperature	Room
Time	10 min

Pretreatments: Degreasing
Posttreatments: Electroless nickel plating
Remarks: The stronger solutions above are for magnesium alloys containing aluminum. The other solution is for other alloys.

ELECTROLESS NICKEL BATH

Type of Treatment or Coating: Metallic coating
Process Name: Electroless nickel
Use: For plating nickel on magnesium alloys; for plating aluminum, steel, copper, or brass
Protective Value:
Abrasion resistance: 350–400 and up to 640 Vickers Pyramid Number by heat treatment
Type of Bath: Immersion
Bath Composition:

$2NiCO_3 \cdot 3Ni(OH)_2 \cdot 4H_2O$	10 g/liter
HF (70%)	6 ml/liter
Citric acid ($C_6H_8O_7$)	5.5 g/liter
NH_4HF_2	15 g/liter
$NaH_2PO_2 \cdot H_2O$	20 g/liter
NH_4OH (30%)	30 ml/liter
Water	To make 1 liter

Operating Conditions:

Temperature	170° to 180° F
pH	4.5 to 6.8 (6.5)
Agitation	Agitate work

Deposition Rate of Coating: 0.0008 in./hr
Tank Material: Polyethylene, Lucite, Saran (tank should be heated by hot water or hot air)
Posttreatments: Stress-relieve at 350° F for 2 hr
Remarks: pH adjusted; with NH_4OH. Add the nickel carbonate to the HF, then add about 100 milliliters water to form $NiHF_2$; then add water and other chemicals. Filter final solution.

DIRECT NICKEL ELECTROPLATING

Type of Treatment: Nickel plating magnesium
Use: For plating directly on magnesium alloys
Type of Bath: Electroplating
Bath Composition:

HF (70%)	61.5 ml/liter
$2NiCO_3 \cdot 3Ni(OH)_2 \cdot 4H_2O$	120 g/liter
Citric acid ($C_6H_8O_7$)	40 g/liter
Sodium lauryl sulfate	1.0 g/liter
Water	To make 1 liter

Operating Conditions:

Temperature	120° to 140° F
pH	3.0 (1.0 to 3.0)
Current density	30 to 100 A/sq ft
Cathode agitation	12 to 16 ft/min

Appearance of Coating: Semibright metallic
Thickness of Coating: 0.0001 to 0.0003 in.
Posttreatments: Chemical etch.

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