
MAGNESIUM ALLOY DEVELOPMENT FOR
HIGH-TEMPERATURE AUTOMOTIVE APPLICATIONS
Mihriban Pekguleryuz
McGill University
Metals & Materials Engineering
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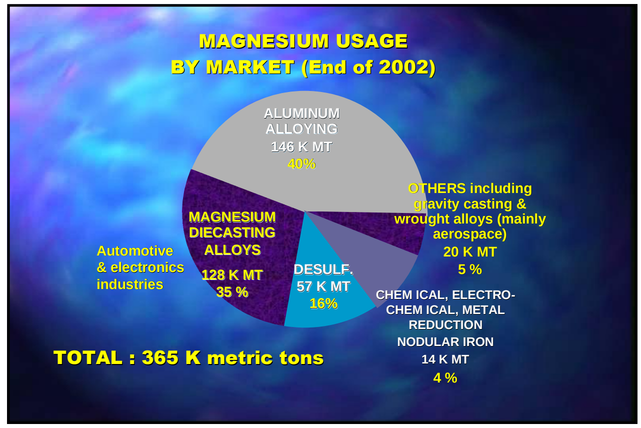
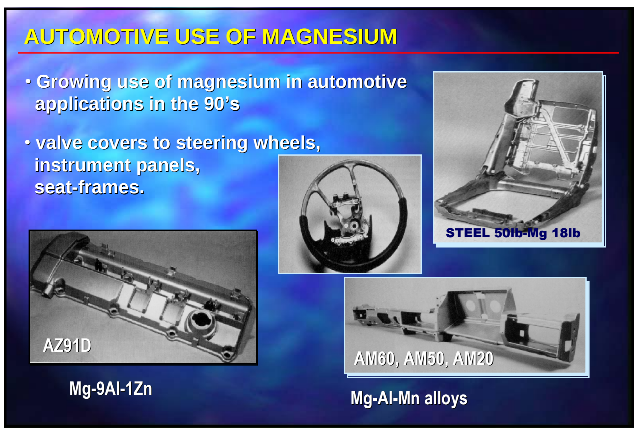
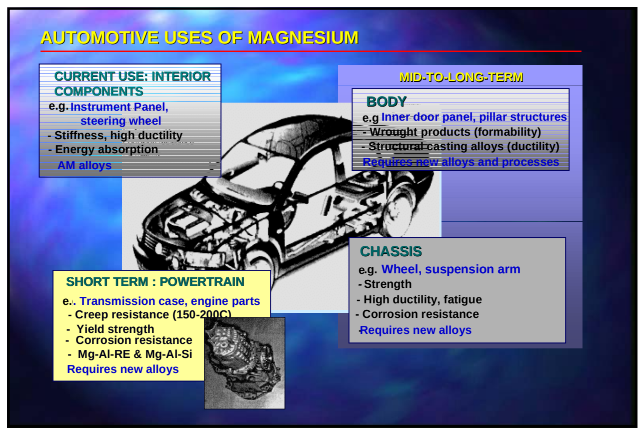
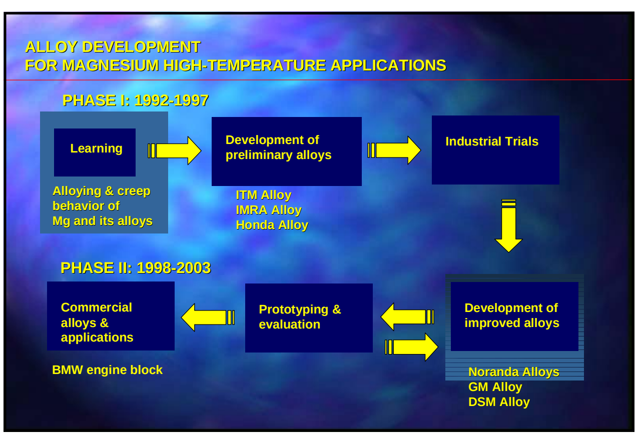
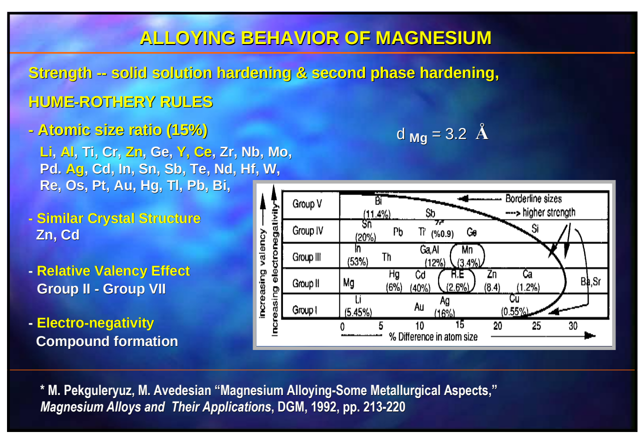

MAGNESIUM USAGE
BY MARKET (End of 2002)
ALUMINUM ALLOYING
146 K MT
40%
MAGNESIUM DIECASTING ALLOYS
128 K MT
35 %
Automotive & electronics industries
DESULF.
57 K MT
16%
OTHERS including gravity casting & wrought alloys (mainly aerospace)
20 K MT
5 %
CHEM ICAL, ELECTRO-CHEM ICAL, METAL REDUCTION
NODULAR IRON
14 K MT
4 %
TOTAL : 365 K metric tons


AUTOMOTIVE USE OF MAGNESIUM
• Growing use of magnesium in automotive applications in the 90's
• valve covers to steering wheels, instrument panels, seat-frames.
STEEL 50lb-Mg 18lb
AZ91D
Mg-9Al-1Zn
AM60, AM50, AM20
Mg-Al-Mn alloys


AUTOMOTIVE USES OF MAGNESIUM
CURRENT USE: INTERIOR COMPONENTS
e.g. Instrument Panel, steering wheel
- Stiffness, high ductility
- Energy absorption
AM alloys
MID-TO-LONG-TERM
BODY
e.g Inner door panel, pillar structures
- Wrought products (formability)
- Structural casting alloys (ductility)
Requires new alloys and processes
SHORT TERM : POWERTRAIN
e.. Transmission case, engine parts
- Creep resistance (150-200C)
- Yield strength
- Corrosion resistance
- Mg-Al-RE & Mg-Al-Si
Requires new alloys
CHASSIS
e.g. Wheel, suspension arm
- Strength
- High ductility, fatigue
- Corrosion resistance
Requires new alloys


ALLOY DEVELOPMENT
FOR MAGNESIUM HIGH-TEMPERATURE APPLICATIONS
PHASE I: 1992-1997
Learning
Alloying & creep behavior of Mg and its alloys
Development of preliminary alloys
ITM Alloy
IMRA Alloy
Honda Alloy
Industrial Trials
PHASE II: 1998-2003
Commercial alloys & applications
BMW engine block
Prototyping & evaluation
Development of improved alloys
Noranda Alloys
GM Alloy
DSM Alloy


ALLOYING BEHAVIOR OF MAGNESIUM
Strength -- solid solution hardening & second phase hardening,
HUME-ROTHERY RULES
- Atomic size ratio (15%)
d Mg = 3.2 Å
Li, Al, Ti, Cr, Zn, Ge, Y, Ce, Zr, Nb, Mo,
Pd. Ag, Cd, In, Sn, Sb, Te, Nd, Hf, W,
Re, Os, Pt, Au, Hg, Tl, Pb, Bi,
- Similar Crystal Structure
Zn, Cd
- Relative Valency Effect
Group II - Group VII
- Electro-negativity
Compound formation
Group V
Group IV
Group III
Group II
Group I
Bi (11.4%)
Sb
Sn (20%)
Pb
Ge
Si
In (53%)
Th
Ga,Al (12%)
Mn (3.4%)
Mg
Hg (6%)
Cd (40%)
R.E (2.6%)
Zn (8.4)
Ca (1.2%)
Ba,Sr
Li (5.45%)
Au
Ag (16%)
Cu (0.55%)
Borderline sizes
higher strength
increasing valency
increasing electronegativity
0 5 10 15 20 25 30
% Difference in atom size
* M. Pekguleryuz, M. Avedesian "Magnesium Alloying-Some Metallurgical Aspects,"
Magnesium Alloys and Their Applications, DGM, 1992, pp. 213-220

ALLOYING BEHAVIOR OF MAGNESIUM

- Elements that Increase both Strength and Ductility

  Strength Criterion : Al, Zn, Ca, Ag, Ce, Ga, Ni, Cu, Th, Y

  Ductility Criterion : Th, Y, Ga, Zn, Ag, Ce, Ca, Al, Ni, Cu

- Elements that Increase Strength at the Cost of Ductility

  Sn, Pb, Bi, Sb

- Elements that Increase Ductility but not Strength

  Cd, Tl, Li, Mn

- Creep

  RE, Y, Ca, Cu, Th, Ag

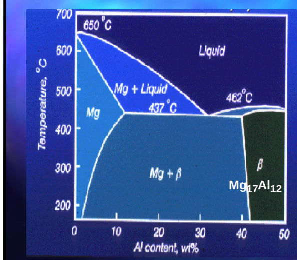
Mg-Al & Mg-Al-Zn ALLOYS

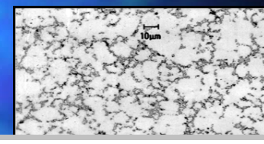
AZ91, AM20, AM50, AM60 casting alloys

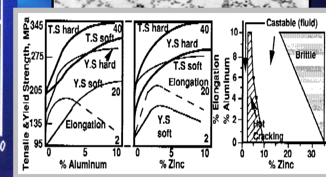
AZ31, AZ61 wrought alloys

AZ80 forging alloy

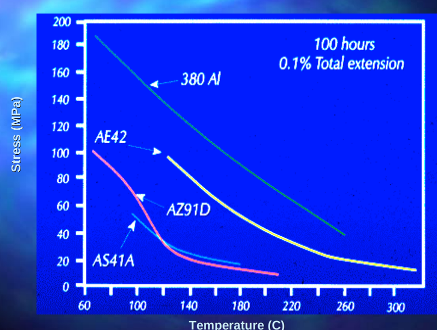
Precipitation hardening alloys
Good R.T strength & ductility
LOW CREEP RESISTANCE







CREEP STRENGTH OF Mg DIECASTING ALLOYS



CREEP DEFORMATION

CREEP -- THE TIME DEPENDENT STRAIN

- slow, continuous deformation with time.

  $\varepsilon = f(\sigma)$ elastic/plastic deformation,

  $\varepsilon = f(\sigma, T, t)$ creep deformation

Due to the thermally activated stress component (short range component)

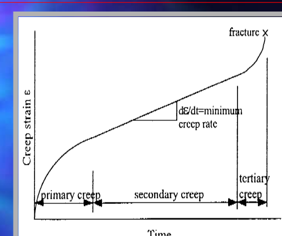
$\sigma = \sigma_u + \sigma^*$

$\tau = \tau_u + \tau^*$

CREEP RATE

strain rate at a given stress is temperature sensitive.

$\dot{\varepsilon} = A\, e\,(-q/kT).\ e(v\tau^*/kT)$



Dislocation Creep $\dot{\varepsilon} = A\,\sigma^n\, e\,(-Q/RT)$

dislocation intersection, dislocation climb, movement of dislocation atmospheres, cross-slip, grain-boundary shear.

Diffusion-Creep $\dot{\varepsilon} = B\,\sigma\, e\,(-Q/RT)$

fast diffusion paths (dislocation cores or GB) or bulk diffusion (vacancy and interstitial) (q_d or q_s) T> 0.3 T_m

CREEP MECHANISMS--*What can be Thermally Aided ?*

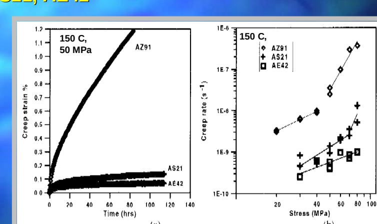
• **Dislocation Intersection** - work required to force a dislocation through the stress field of another can be thermally aided. Mg single crystals	$\dot{\varepsilon} = A\, e\, [-(q_i - \tau^* b^2 l)/kT]$
• **Activated Cross Slip** - Thermally activation to unite partial dislocations and to breakdown into partials on different slip systems.	q =100 kJ/mol for high stacking fault metals
• **Movements of Dislocations with jogs** - formation (q_j) and movement (q_m) of vacancies. Self diffusion ($q_d = q_j + q_m$).	$\dot{\varepsilon} = A\, e\, [-(q_d - \tau^* b^2 x)/kT]$ q_d Mg 135 kJ/mol, q Mg 125 kJ/ mol.
• **Dislocation Climb** - Climb of dislocations over sessile dislocations or precipitates. Vacancy diffusion to and from edge dislocations (q_d) and formation of jogs (q_j). Activation energy, $q = q_d + q_j$	$\dot{\varepsilon} = A\sigma^{\alpha}\, e\,(-q_d)/kT$ $\dot{\varepsilon} = Be^{\beta\sigma}\, e\,(-q_d)/kT$ q in the range of q_d (135kJ/mol)
•**Movement of Dislocation Atmospheres** - Diffusion of solute atoms and the viscous behavior of the solute atmosphere	$\dot{\varepsilon} = A\,\sigma\, e\,(-q_s)/kT$ q_{Al} in Mg 143 kJ/mole

•**Grain Boundary Shear** - relative movement of grains, deformation in very narrow region adjacent to the GB, the shear direction lies in the boundary with the max resolved shear stress. Affective at high temperatures, usually when the recovery temperature is achieved. Discontinuous. GBs recover before the grains, softening. Accounts for 30% of the deformation.

Grain boundary diffusion: 80 kJ/mol.

CREEP BEHAVIOR OF Mg DIECASTING ALLOYS

AZ91D, AS21, AE42



M. S. Dargusch, G.L.Dunlop, K. Pettersen, *Proc of Conf. on Magnesium Alloys and their Applications*,"
B.L. Mordike and K.U. Kainer, Eds,, Wolsburg, Germany, 1998 pp. 277-282.

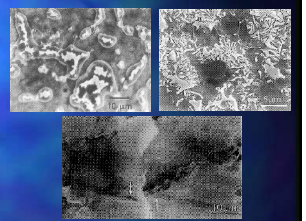
CREEP BEHAVIOR OF Mg-Al ALLOYS (AZ, AM)

AZ91D -- Activation energy in $\dot{\varepsilon} = A\sigma^n \exp(-Q/RT)$, 125-175°C, 50 MPa was 30-45 $kJmol^{-1}$, n=2

self-diffusion of Mg (135 $kJmol^{-1}$) or diffusion of Al in Mg (143 $kJmol^{-1}$) or grain boundary diffusion (80 $kJmol^{-1}$)

Q for discontinuous precipitation of $Mg_{17}Al_{12}$ = 30 kJ/mol
Creep induced $Mg_{17}Al_{12}$ aids easy grain boundary sliding and migration.

At higher stresses: 95 kJ/mol, n = 5
Activated cross slip
Dislocation intersection ?

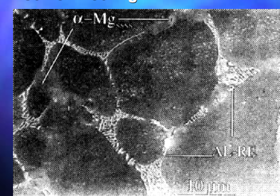


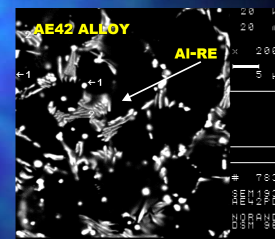
M. S. Dargusch, G.L.Dunlop, K. Pettersen, *Proc of Conf. on Magnesium Alloys and their Applications*," B.L. Mordike and K.U. Kainer, Eds., Wolsburg, Germany, 1998 pp. 277-282.

CREEP BEHAVIOR OF Mg-Al-RE ALLOYS (AE)

Mg-Al-RE

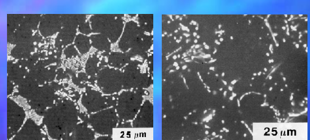
- Activation energy 35-40 $kJmol^{-1}$
- Higher creep resistance
- Stable Al-RE containing phases
- No $Mg_{17}Al_{12}$ phase but some Al coring





M. S. Dargusch, G.L.Dunlop, K. Pettersen, *Proc of Conf. on Magnesium Alloys and their Applications*," B.L. Mordike and K.U. Kainer, Eds,, Wolsburg, Germany, 1998 pp. 277-282.

Metallurgical Stability in Mg-Al-RE ALLOYS (AE)



(a) (b)
Microstructure of AE42 (a) diecast (b) after 175C exposure

T (C)	Mg	$Al_{11}RE_3$	Al_2RE	$Mg_{17}Al_{12}$
As-cast 25C	97.5	1.8	0.8	0.0
150 C	97.7	1.5	0.8	0.0
175 C	97.0	1.2	1.3	0.6

Ref : B. R. Powell, V. Rezhets, M.P. Balogh, and R.A. Waldo, "Microstructure and Creep Behavior in AE42 Magnesium Die-Casting Alloy", Journal of Metals, TMS, August 2002, pp. 34-38

ALLOY DESIGN FOR CREEP IN Mg DIECASTING ALLOYS

GENERAL PRINCIPLES

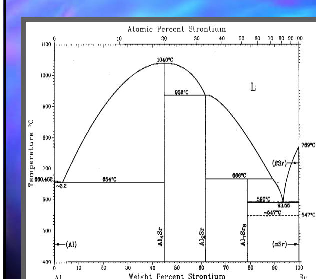
AVOID	$Mg_{17}Al_{12}$	
	creep induced precipitation, e.g. $Mg_{17}Al_{12}$	
	aging, microstructural instability	Sr, Ca, RE
STRONG GRAIN BOUNDARIES		
High temperature surface active solutes		Sr, Ca, RE
Second phases (line compounds,		Sr, Ca, RE
coherent particles)		Sb, Bi
MICROSTRUCTURAL MODIFICATION		Sr, Ca, RE
		Sb, Bi, Sn

* M. Pekguleryuz, M. Avedesian "Magnesium Alloying-Some Metallurgical Aspects," *Magnesium Alloys and Their Applications*, DGM, 1992, pp. 213-220

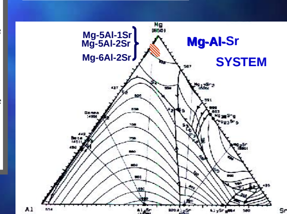
RATIONALE FOR ALLOY SYSTEM SELECTION

- AVOID COSTLY OR RARE ELEMENTS (Sc, Rare earths, Ag, etc)
- MAINTAIN ALUMINUM FOR GOOD DIE CASTABILITY (5-6%)
- USE ALKALINE EARTH ELEMENTS (Ca, Sr)
  - second phases for grain boundary pinning
  - solute segregation
- AVOID ELEMENTS THAT CAN ADVERSELY EFFECT CORROSION (Cu, Ni)
- CHOOSE TERNARY SYSTEMS FOR SIMPLICITY & COST AND EASE OF MANUFACTURING
- Mg-Al-Sr SELECTED AS THE OPTIMUM ALLOY SYSTEM TO DEVELOP

GRAIN BOUNDRY PINNING



AL_4Sr
Space Group: I4/mmm
Body centered tetragonal
a = 0.445 nm c = 1.105 nm



Mg-Al-Sr ALLOY COMPOSITIONS

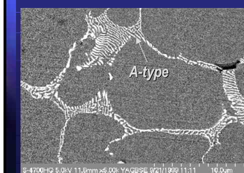
Alloy designation : AJ Alloys where J designates Sr

ALLOY	Al wt. %	Sr wt. %
AJ51x	4.5 - 5.5	1.2- 1.5
AJ52x	4.5 - 5.5	1.6- 2.3
AJ62x	5.5 -6.5	2.0- 2.6
AJ62Lx	5.6 -6.6	1.5- 1.9

Microstructure of Diecast AJ Alloys

AJ51x
AJ62Lx

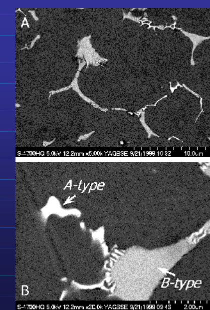
α-Mg solid solution and a lamellar intermetallic (Type A)



Sr/Al < 0.3

AJ52x
AJ62x

α-Mg and
Type A
Type B
intermetallics



Sr/Al > 0.3

Mg-Al-Sr Alloy Phases

Using XRD coupled with analytical STEM

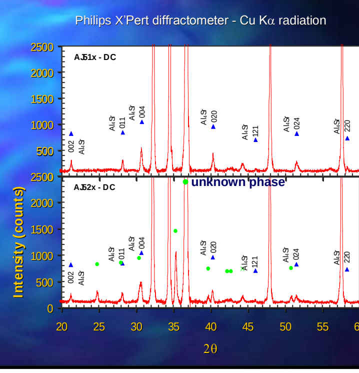
AJ62x, AJ51x:

Type-*A* compound is isomorphous to Al_4Sr and Al/Sr ratio is close to Al_4Sr with some Mg in solution.

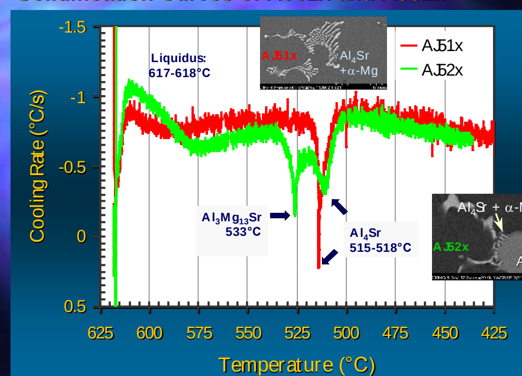
AJ52x:

Type-*A* compound corresponds to Al_4Sr with 15 wt.% Mg.

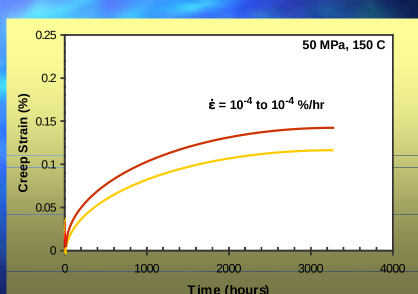
Type-*B* compound does not correspond to any known crystal. Tentative : 3Al.13Mg.Sr



Solidification Curves of AJ51x and AJ52x

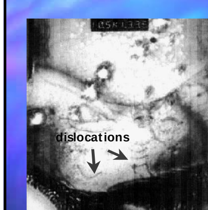


TYPICAL CONSTANT LOAD CREEP CURVES



* E. Landriaut, Ecole Polytechnique, M.Eng. Thesis

CREEP DEFORMATION IN AJ52x



CREEP DEFORMATION

50 MPa, 150 C, 500 hours creep samples shows very little dislocation pile up, and some sub-grain formation

ACTIVATION ENERGY *

150-175C, 35-100 MPa range

Q = 32-25 kJ/mol

POSSIBLE MECHANISMS

- Sub-grain formation (stress activated recovery)
- Precipitation induced creep ? (change in relative fractions of phases)
- Grain migration ?

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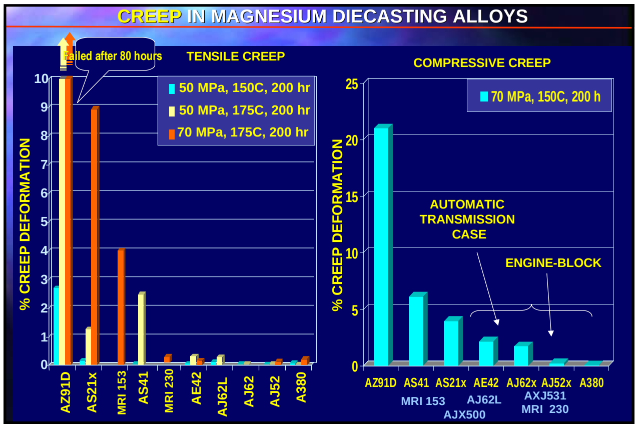
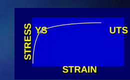
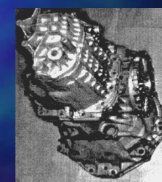
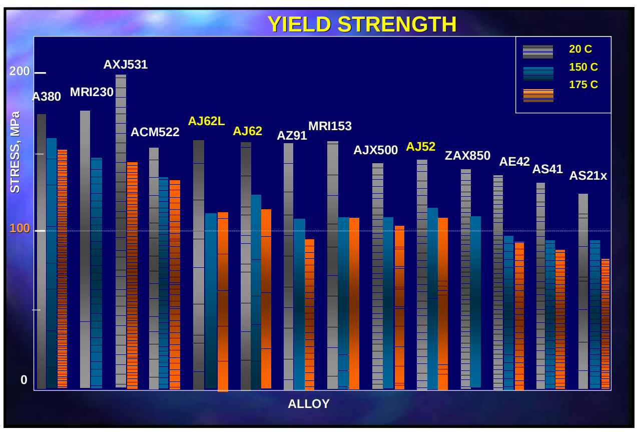


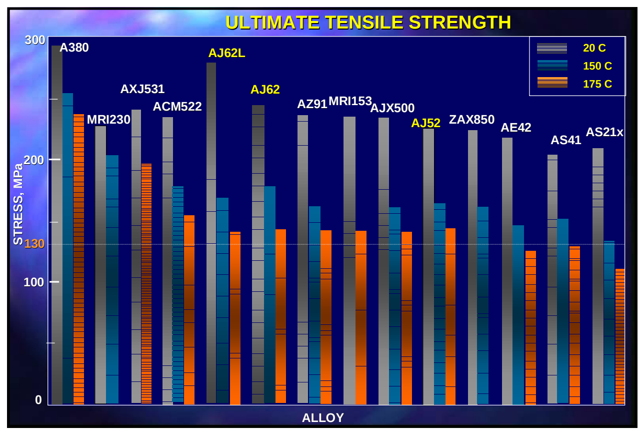
PERFORMANCE REQUIREMENTS FOR DIECASTING ALLOYS

- Creep resistance (tensile & compressive) up to 175°C (min creep rate)
- Bolt-load retention up to 175°C (50% min)
- Metallurgical / thermal stability
- Tensile yield strength up to 175°C (100 MPa)
- Fatigue resistance (fatigue limit at 175 ° C : 45 MPa min)
- Ultimate tensile strength up to 175°C (130 MPa)
- Salt-spray corrosion resistance (0.1-0.25 mg/cm^2/day)
- Elongation (min 3% at room temperature)
- Acceptable diecastability (comparable to AM or AE)
- Acceptable cost (5-10 ¢over alloy prices)
- Availability of raw materials
- Alloy production (compatibility with plant processes)
- Melt handling (oxidation, sludge formation)
- Recyclability



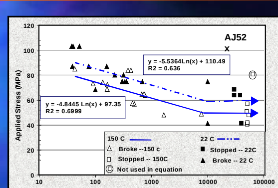


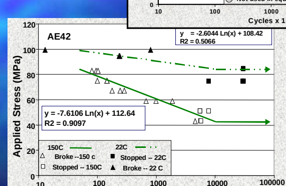




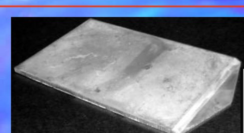
OTHER PROPERTIES OF AJ ALLOYS

- High thermal conductivity :
  75-95 W/m K, 22-450 C (AZ91D : 58-78 W/m K)
- High fatigue resistance
  at elevated temperature
- Good fracture toughness
- Fluxless Recycling
- Compatible with
  most cover gases



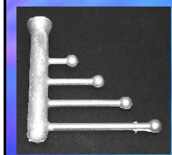


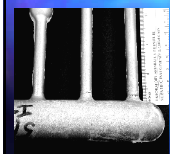
CORROSION PROPERTIES OF MAGNESIUM DIECASTING ALLOYS



ALLOY	CORROSION RATE (mg/cm^2 /day)
AZ91D	0.10
AE42	0.21
AS41	0.16
AJ62x	0.11
AJ52x	0.09
AJ62Lx	0.04
MRI 153	0.09
MRI 230	0.10
A380	0.34

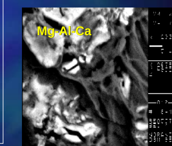
CASTABILITY IMPROVEMENT





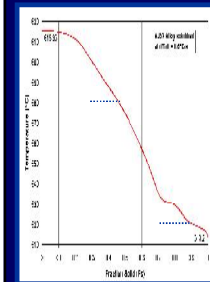
ALLOY	AVERAGE HOT TEAR RATING*
A380	2
AZ91D	20
AZ91E	14
AM50A	44
AM60A	31
ITM alloy (0.8%Ca)	61
AJ50x (0.2Ca, 0.5Sr)	45-60
AS21	69
AS21x	27
AS41B	82
AE42	95
AJ51x	35-50
AJ52x	24
AJ53x	5
AJ62x	2
AJ62Lx	0

*A lower number means less susceptibility to hot tearing



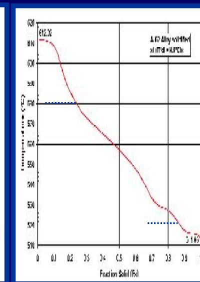
CASTABILITY IMPROVEMENT

Fraction Solid Evolution



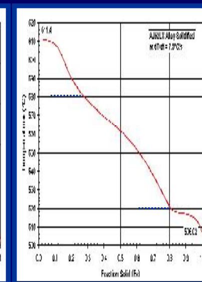
AJ52x

ΔH = 450 J/kg



AJ62x

ΔH = 500 J/kg



AJ62Lx

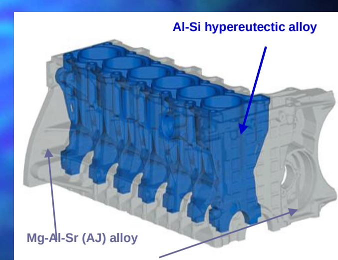
ΔH = 530 J/kg

DIECASTABILITY OF AJ ALLOYS

ALLOY	Die Sticking	Cracking	Fluidity	Overall Rating
AJ52x	low	Low	Good	Good. If recommended parameters are used very good castability can be obtained.
AJ62x	Very low	none	Similar to AM	Very good
AJ62Lx	Very low	none	Similar to AM AZ	Excellent

BMW ENGINE BLOCK

- First commercialization of a Mg alloy in engine applications
- Hybrid engine block with Al insert and Mg block
- 10,000 MT of annual usage
- BMW has 3 years of exclusive rights to the AJ alloy patent for use in engine applications



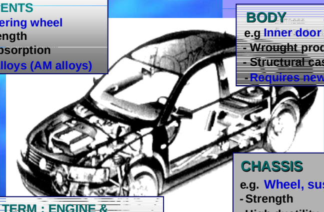
AUTOMOTIVE USES OF MAGNESIUM

CURRENT USE: INTERIOR COMPONENTS
e.g. IP, steering wheel
- Yield strength
- Energy absorption
- existing alloys (AM alloys)

MID-TO-LONG-TERM

BODY
e.g Inner door panel, pillar structures
- Wrought products (formability)
- Structural casting alloys (ductility)
- Requires new alloys and processes

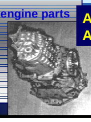
AJ62Lx



CHASSIS
e.g. Wheel, suspension arm
- Strength
- High ductility
- Corrosion resistance
- Requires new alloys

SHORT TERM : ENGINE & TRANSMISSION
e.g Transmission case, engine parts
- Creep resistance
- Stiffness
- Corrosion resistance
- AE, AS alloys
- Requires new alloys
- Potential use 60 000tpy

AJ52
AJ62



FUTURE WORK IN Mg ALLOYS

Creep Resistant Alloys

Investigate creep mechanisms in new alloys
Investigate microstructural evolution during creep
Creep design for higher temperatures
Castability research on existing alloys

High Ductility Alloys

Improved ductility of the primary phase with solute additions
Modified AJ62Lx type alloys

Mg Wrought Alloys

Understanding texture, formability, recovery, microstructure effects in existing alloys
Alloy modification as it relates to recovery and formability
The role of trace elements
Low Li (2%) with trace elements
The role of Mn
Effect of solutes
Grain refining and prevention of grain growth with trace elements
Modify surface texture for bending
Understanding twin roll casting, rolling, bending operations

Partial Castability Index

Castability index for thin walled parts:	$0.1(\Delta F) + 0.4\Delta\kappa + 0.3\,\Delta HTS + 0.2\Delta T'$
Castability index for medium walled parts :	$0.1(\Delta F) + 0.2\,(\Delta\kappa) + 0.4\,\Delta HTS + 0.2\,\Delta T''$
Castability index for thick-walled castings :	$0.2(\Delta F) + 0.3\,\Delta\kappa + 0.4\,\Delta HTS - +0.2\,\Delta T'$

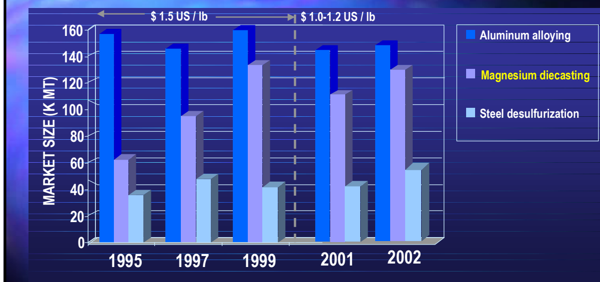
where, ΔF = (freezing range for AZ91) – (freezing range for alloy)

$\Delta\kappa$ = (thermal conductivity of alloy) – (thermal conductivity of AZ91)

ΔHTS = (Hot-tear sensitivity of AZ91) – (hot-tear sensitivity of alloy)

$\Delta T'$ = (near equilibrium freezing-range of alloy) – (60°C)

MARKET GROWTH



Highest market growth potential is in magnesium diecasting alloys used in automotive and electronics applications (6-9%)

TENSILE CREEP IN AJ & OTHER Mg ALLOYS

ALLOY	% Creep @ 50 MPa, 200 hrs		% Creep @ 50 MPa, 500 hrs		% Creep @ 70 MPa, 200 hrs (Ref)
	150 C	175 C	150 C	175 C	175 C
AJ52x	0.04	0.05	0.03	0.09	0.14
AJ62x	0.05	0.05	-	-	-
AJ62Lx	0.13	0.29	-	-	-
AE42	0.06	0.33	0.08	0.44	0.18
AS41	0.05	2.48	0.07	-	-
AS21x	0.19	1.27	-	-	8.95
AZ91D	2.7	*	6.35	-	-
A380	0.08	0.04	0.10	0.05	0.22**

*failed after 80 hrs **A383 alloy

Ref : A. P. Druschitz, E. R. Showalter, J.B. McNeill, D. L. White, "Evaluation of Structural and High-Temperature Magnesium Alloys", SAE Paper 2002-01-0080.

COMPRESSIVE CREEP IN AJ & OTHER Mg ALLOYS

ALLOY	% COMPRESSIVE CREEP @ 150C, 70 MPa, 200 hrs	% BOLT LOAD RETENTION 70 MPa, 100 hours (Ref)	
		150 C	175C
AJ52x	0.24	73%	49%
AJ62x	1.73	-	-
AE42	2.16	65%	50%
AS41	6.13	-	-
AS21x	3.97	55%	29%
AZ91D	21	-	-
A380	0.03	-	81% *

*A383 alloy

Ref : A. P. Druschitz, E. R. Showalter, J.B. McNeill, D. L. White, "Evaluation of Structural and High-Temperature Magnesium Alloys", SAE Paper 2002-01-0080.

DESIGN PRINCIPLES FOR CREEP-RESISTANT ALLOYS

1. MINIMIZE RECOVERY AND SOFTENING EFFECTS;

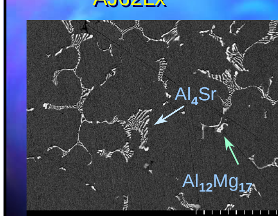
•SOLID-SOLUTION HARDENING $T=0.3T_m$

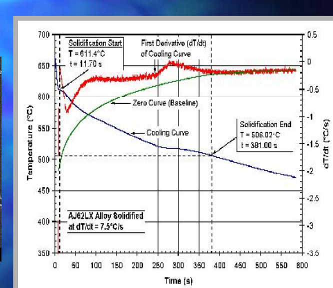
Element	Solid-solubility limit (wt%)	Melting point, °C
Zinc	~ 2% at 20-150°C and 6.2% at 325°C	420
Aluminum	2 % at 20°C; 3% at 200°C and 12.6 % at 437°C	660
Rare Earths (Ce)	Negligible at 20°C and 0.15 % at 337°C	798
Calcium	Negligible at 20°C and 0.5% at 250°C	840
Copper	No solid solubility of Cu in Mg	1085
Manganese	Negligible at 20°C and < 0.1 % below 300°C	1246
Silicon	No solid solubility of Si in Mg	1414
Yttrium	1.8-2% at 200°C and 6.5% at 566°C	1528
Zirconium	0.2% at 300°C and 3.5% at 654°C	1865

• PRECIPITATION HARDENING DEPENDS ON HEAT-TREATMENT AND CANNOT BE APPLIED TO DIECAST MATERIALS DUE TO BLISTERING

AJ62Lx Microstructure

AJ62Lx



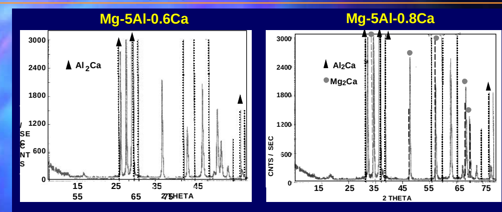


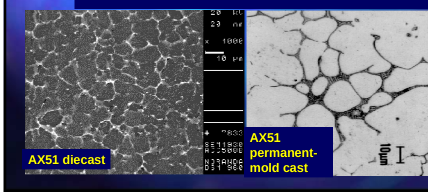
CHARACTERISTICS OF SECOND PHASES IN Mg DIECASTING ALLOYS

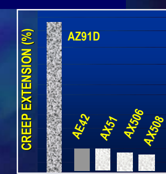
ALLOY	SECOND PHASES			CREEP INDUCED PRECIPITATION	CREEP RESISTANCE
	PHASE	TYPE	MELTING POINT		
Mg-Al (AM) Mg-Al-Zn (AZ91)	$Mg_{17}Al_{12}$	42- 58% Al Incoherent with α-Mg	437°C	$Mg_{17}Al_{12}$ (eutectoid)	Low
Mg-Al-Si	$Mg_{17}Al_{12}$ Mg_2Si	See above Line compound**	1085°C	$Mg_{17}Al_{12}$ (eutectoid)	Borderline
Mg-Al-RE (AE42)	Al_2RE $Al_{11}RE_3$	Line compounds**	1480°C	$Mg_{17}Al_{12}$ and Al_2RE (above 150 °C)	Good
Mg-Al-Ca	Al_2Ca	Line compound **	1079°C	-	Good
Mg-Al-RE-Ca-Mn	Al_2RE, $Al_{11}RE_3$ Al_2Ca Mn-Al-RE & Al-Ca-RE Intermetallics (Al-Mn-Ce) and/or Al-Mn-La intermetallics	Line compounds** Line compound**	1480°C 1079°C	-	Good
Mg-Al-Sr	Al_4Sr and Al-Mg-Sr		1040°C	-	Good

**(Laves phase)

Mg-Al-Ca ALLOYS (AX)







ALLOYS DEVELOPED IN 1992-2002

ALLOY	DESIGNATION	INVENTOR	STATUS / COMMENTS
Mg-Al-Si	AS41 (Mg-4Al-1Si) AS21 (Mg-2Al-1Si)	VW	Commercial
Mg-Al-Si (RE)	AS21x	Hydro Mag.	PATENTED
Mg-Al-RE	AE42 (Mg-4Al-2 RE)	Dow	Commercial
Mg-Al-Ca	AX51 {Mg-5Al-(.2-.8)Ca}	ITM	WO96/25529 (1995), PD*
Mg-Al-RE-Ca	AEX ACM522--(Mg-5Al-2RE-2Ca)	Nissan-UBE Honda	EP 0799901 A1 (1997) NK** EP 0791 662A1 (NK**)
Mg-RE-Ca (Mn)	EX {Mg-(2-5)RE-(0-1)Ca}	MEL	WO96/24701 (NK**)
Mg-Zn-Al-Ca	ZAX850	IMRA	US 5855697 (1999)
Mg-Al-RE-Ca (Sr)	MRI 153, MRI 230D	DSM-VW	US 6139651 (2000)
Mg-Al-Sr	AJ {Mg-(2-9)Al-(.5-7)Sr}	Noranda	US 6322644 (2001)
Mg-Al-Ca-Sr	AXJ {Mg-5Al-(2-3)Ca-0.07Sr	GM	US 6264763 (2001)
Mg-Al-Sr-Ca	AJX {Mg-(2-9)Al-(.2-.6)Sr-(.15-.3Ca)	Noranda	US 6342180 (2002)

* PD: public domain ** NK: status not known

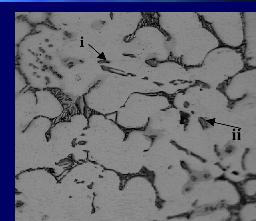
MICROSTRUCTURES OF RARE-EARTH & CALCIUM CONTAINING (NISSAN, HONDA, DSM) ALLOYS

ACM522 (Mg-5Al-2Ca-2RE)
MRI 153

high melting-point second phases

Al-(RE, Ca) compounds

Interaction of stable phases with dislocations and grain-boundary pinning



HONDA PATENT
Mg-8%Al-2.5%RE-1.6%Ca-1.3%Mn
permanent-mold cast

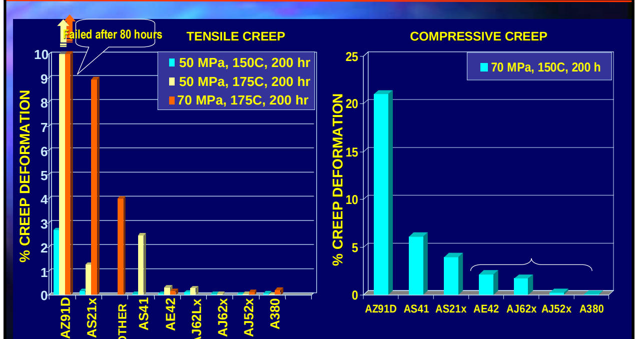
Al_2Ca lamellar phase, needle shaped Al-RE (Ca, Mn) and Al-Mn-RE intermetallics

TENSILE PROPERTIES OF AJ & OTHER Mg ALLOYS

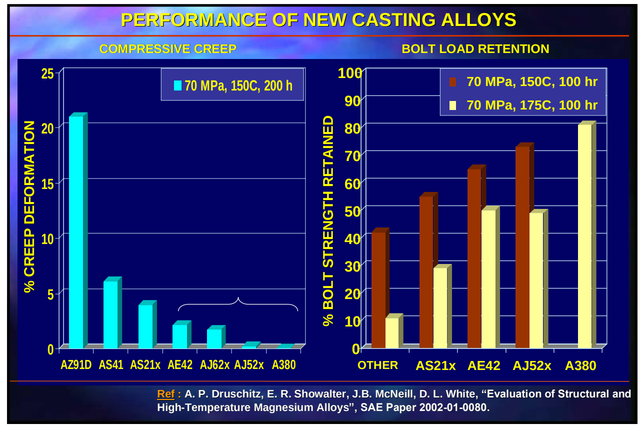
PROPERTY	ALLOY							
	A380	AJ62x	AJ52x	AJ62Lx	AE42	AS41	AS21x*	AZ91D
YIELD STRENGTH (MPa)								
20 C	155 (180)	143	134	152	128(145)	136 (140)	121	139 (160)
150 C	154 (159)	108	110	116	88 (100)	94 (95)	87	105 (108)
175 C	148 (148)	103	100	109	81 (91)	85 (85)	78	89
ULTIMATE TENSILE STRENGTH (MPa)								
20 C	290 (290)	240	212	276	220 (230)	197 (215)	210	204 (240)
150 C	251 (257)	163	163	166	140 (157)	153 (155)	130	169 (157)
175 C	248 (228)	143	141	143	121 (130)	127 (127)	110	138
ELONGATION (%)								
20 C	3.2 (3)	7	6	12	10 (11)	4 (6)	5.5	3.1 (3)
150 C	6.4 (7)	19	12	27	23 (20)	17 (24)	20	16 (23)
175 C	7.1 (10)	19	18	27	23 (23)	19 (25)	23	21

*Ref : A. P. Druschitz, E. R. Showalter, J.B. McNeill, D. L. White, "Evaluation of Structural and High-Temperature Magnesium Alloys", SAE Paper 2002-01-0080

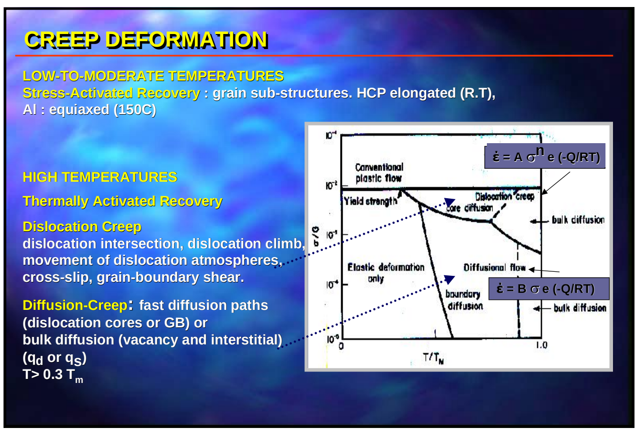
CREEP IN AJ & OTHER Mg ALLOYS



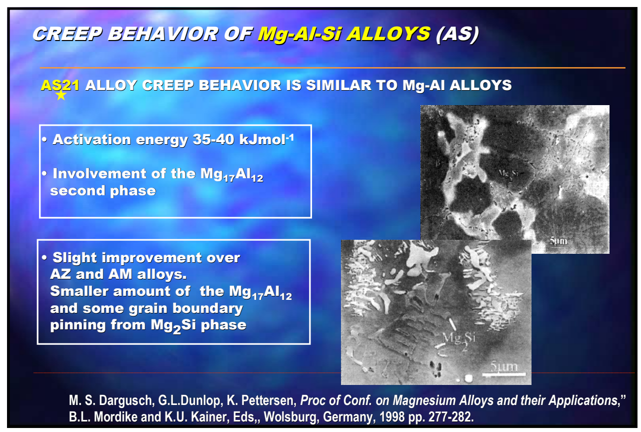
DEVELOPMENT OF
MAGNESIUM-ALUMINUM-STRONTIUM ALLOYS



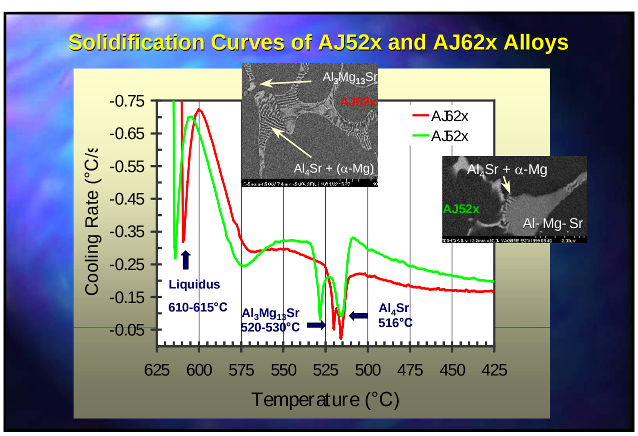
PERFORMANCE OF NEW CASTING ALLOYS
COMPRESSIVE CREEP
BOLT LOAD RETENTION
% CREEP DEFORMATION
70 MPa, 150C, 200 h
AZ91D AS41 AS21x AE42 AJ62x AJ52x A380
% BOLT STRENGTH RETAINED
70 MPa, 150C, 100 hr
70 MPa, 175C, 100 hr
OTHER AS21x AE42 AJ52x A380
Ref : A. P. Druschitz, E. R. Showalter, J.B. McNeill, D. L. White, "Evaluation of Structural and High-Temperature Magnesium Alloys", SAE Paper 2002-01-0080.



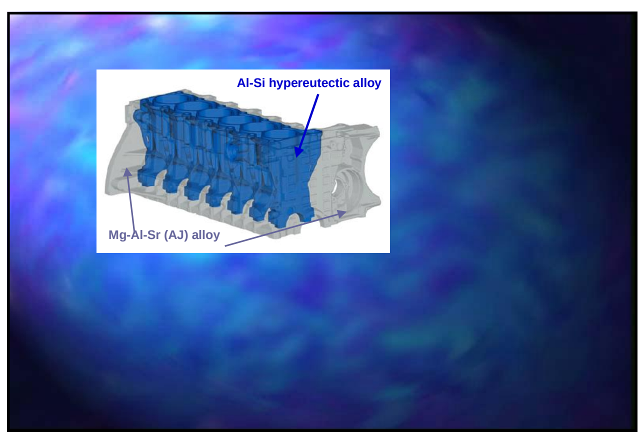
CREEP DEFORMATION
LOW-TO-MODERATE TEMPERATURES
Stress-Activated Recovery : grain sub-structures. HCP elongated (R.T), Al : equiaxed (150C)
HIGH TEMPERATURES
Thermally Activated Recovery
Dislocation Creep
dislocation intersection, dislocation climb, movement of dislocation atmospheres, cross-slip, grain-boundary shear.
Diffusion-Creep: fast diffusion paths (dislocation cores or GB) or bulk diffusion (vacancy and interstitial) (q_d or q_S)
T> 0.3 T_m
$\dot{\varepsilon} = A\,\sigma^n\,e\,(-Q/RT)$
$\dot{\varepsilon} = B\,\sigma\,e\,(-Q/RT)$
Conventional plastic flow
Yield strength
Dislocation creep
core diffusion
bulk diffusion
Elastic deformation only
Diffusional flow
boundary diffusion
bulk diffusion
σ/G
T/T_N



CREEP BEHAVIOR OF Mg-Al-Si ALLOYS (AS)
AS21 ALLOY CREEP BEHAVIOR IS SIMILAR TO Mg-Al ALLOYS
• Activation energy 35-40 kJmol^{-1}
• Involvement of the $Mg_{17}Al_{12}$ second phase
• Slight improvement over AZ and AM alloys. Smaller amount of the $Mg_{17}Al_{12}$ and some grain boundary pinning from Mg_2Si phase
5μm
Mg_2Si
5μm
M. S. Dargusch, G.L.Dunlop, K. Pettersen, Proc of Conf. on Magnesium Alloys and their Applications," B.L. Mordike and K.U. Kainer, Eds,, Wolsburg, Germany, 1998 pp. 277-282.



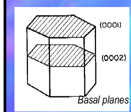
Solidification Curves of AJ52x and AJ62x Alloys
Cooling Rate (°C/s
Temperature (°C)
AJ62x
AJ52x
$Al_3Mg_{13}Sr$
AJ62x
Al_4Sr + (α-Mg)
Al_4Sr + α-Mg
AJ52x
Al-Mg-Sr
Liquidus
610-615°C
$Al_3Mg_{13}Sr$
520-530°C
Al_4Sr
516°C

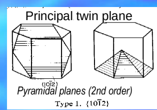


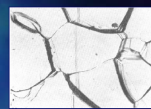
Al-Si hypereutectic alloy
Mg-Al-Sr (AJ) alloy

MECHANISMS OF CREEP PURE MAGNESIUM(90-300°C, 8-70 MPa)*

LOW TEMPERATURES : basal slip, twinning and sub-grain formation, (transient creep)

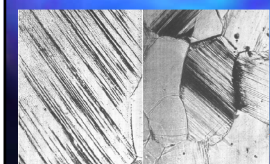


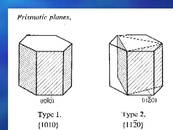


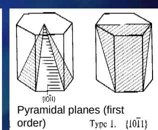


HIGHER TEMPERATURES: non-basal slip, twinning
grain boundary deformation and sliding (steady-state creep)

Q= 65 kJ/mol







* G.V. Raynor, *The Physical Metallurgy of Magnesium and Its Alloys*, Pergamon Press, Oxford, UK, 1959, pp. 247-249, 348.