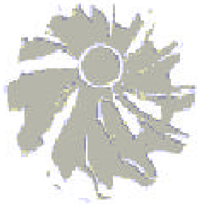

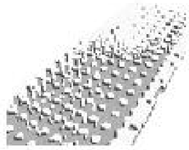

THERMAL TREATMENTS OF AGE-HARDENABLE METAL MATRIX COMPOSITES

MMC-Assess Thematic Network

Volume 2

P.Merle

THERMAL TREATMENTS OF AGE-HARDENABLE METAL-MATRIX COMPOSITES

GENERAL COMMENTS

The age hardening characteristics of an alloy are generally modified by the introduction of a reinforcement. These modifications are due to the manufacturing process, the reactivity between the reinforcement and the matrix, the size, and to the size, morphology and volume fraction of the reinforcement.

-The size, morphology and volume fraction of the reinforcement, are factors controlling the plasticity and the thermal residual stresses in the matrix. The sink effect due to interfaces introduced by the presence of the reinforcement may also play an important role in precipitation kinetics

- The manufacturing process may lead to different microstructures which would also modify the precipitation kinetics

- The reactivity between the reinforcement and the matrix during the elaboration process and during the high temperature solution treatment may lead to a modification of the composition of the matrix. If we take Si, Cu, Mg which are the main alloying elements, the most important reaction phenomena are due to the reactivity of magnesium with the reinforcement, which may lead to a decrease of the content of this element in solid solution and thus to a decrease of the amount of precipitates formed during ageing. Magnesium is highly reactive with silica in the temperature range 500°C-550°C and, to a lesser extent with alumina, whereas no reactivity is observed for the normal treatment conditions with other reinforcements such as B4C and SiC

Generally speaking, at ageing temperatures corresponding to the precipitation of a semi-coherent phase (like β' in Al-Mg-Si alloys or θ' in Al-Cu alloys) the effect of introducing the reinforcement is to accelerate the kinetics of hardening . This acceleration is measured by the ratio $R = \frac{tpHc}{tpHm}$ of times corresponding to peak hardness in the composite (tpHc) and to peak hardness in the unreinforced matrix (tpHm). R depends on the volume fraction of the reinforcement and, to a lesser extent, on the size of the particles and on the homogeneity of their distribution..

There are many different conclusions in previous articles as to the effect of the introduction of a ceramic reinforcement on the kinetics of zone formation during natural ageing or during an artificial ageing at low temperature. They conclude either that there is no effect of the reinforcement on the precipitation kinetics, or that there is a suppression of zone formation or that there is an acceleration of precipitation kinetics (see comments for each class of alloys).

In addition to the modification of precipitation kinetics, it must also be underlined that the temperature domain of the precipitation of a given phase is also modified by the introduction of the reinforcement.

The data below concerns the age-hardening characteristics of composites, the matrix of which is a commonly used heat treatable alloy. When possible, the complete data given here include, for each alloy :

Unreinforced matrix

- composition
- usual thermal treatments : solution treatment , precipitation heat treatment

Composite :

- See Table

	Material & Processing 1	*Solution treatment* 2	*Precipitation heat treatment* 3	*tpHc (h)* 4	*Hv/H0* 5	*R* 6	*Comments* 7
	AA2014/Al_2O_3/20f [10] Saffil Low pressure infiltration	510°C-2h	T6 180°C	24	175/130	1.1	

Column 1 : Type of composite, reference of the literature, quantitative data on the reinforcement, processing conditions

Column 2 : temperature and time of solution treatment

Column 3 : Type of ageing treatment. This column may concern various ageing conditions (for example different temperatures, or different materials with varying size or volume fraction of the reinforcement)

Column 4 : Gives (in hours) either the time corresponding to peak hardness (tpHc) or, in the case of a plateau, the time corresponding to the maximum hardness (t_MHc) of the composite.

Column 5 : Gives the values of peak hardness for the composite (Hv) and for the unreinforced matrix (H0), or, in the case of a plateau, of the maximum hardness for the composite and for the unreinforced matrix. Values given are Vickers hardness. Any other case is indicated by special symbols (Rockwell hardness HR, Brinell hardness HB, 0.2% proof stress (YS-MPa)

Column 6 : Gives the ratio R between the time for peak hardness (or time for maximum harness) for the composite and for the unreinforced matrix (R<1 corresponds to an acceleration of precipitation kinetics in the composite).

Column 7 : Reference of comments

The optimum heat treatment procedure of a metal matrix composite may differ to a large extent from that of the unreinforced alloy. In the absence of data, a Taguchi approach [1], avoiding extensive testing, may be useful to obtain materials with the highest strength values possible.

[1] SAGAIL A., LEISK G. *Heat treatment optimization of Alumina/Aluminium metal matrix composites using the Taguchi approach*, Scripta Metallurgica et Materialia, 26 (1992) p. 871-876

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Al-BASED MATRIX

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UNREINFORCED MATRIX

General schematic precipitation sequence

In alloys containing a copper-magnesium weight ratio >2 the precipitation sequence is :

GPBI zones → GPBII (ordered) zones (or S")→semi-coherent S' precipitates → equilibrium S precipitates ($CuMgAl_2$)

For high Cu contents and with Si, the metastable phase λ' and θ' associated to the equilibrium λ ($Al_5Mg_2Cu_8Si_5$) and θ (Al_2Cu) phase may precipitate

Composition and thermal treatments

Alloy	Composition	Solution treatment	Annealing	Precipitation heat treatment
2009 2009M	Al-3.7Cu-1.4Mg Al—3Cu-0.7Mg-0.5Ag	520°C		T6-190°C-3 to 6h
2014	Al-4.4Cu-0.8Si-0.8Mn-0.5Mg	502°C	413°C	T6-160°C-18h.
2024 2124	Al-4.4Cu-1.5Mg-0.6Mn	493°C	413°C	T6-190°C-8 to 16h.
2219	Al-6.3Cu-0.3Mn-0.18Zr-0.10V-0.06Ti	535°C	415°C	T3 T6-T8 165 to 190°C 18 to 36h

COMPOSITES

	Material & Processing	Solution treatment	Precipitation heat treatment	*tpHc (h)*	*Hv/H0*	*R*	Com ments
	2009						
P R M	AA2009/SiC/20p [1]	495°C-1h	T6 –150°C				(1)
	Varying mean Diameter		Mean diameter 4µm		85/– HR		
	Powder Metallurgy+extrusion		Mean diameter 10µm	64	85/– HR		
			Mean diameter 13µm	64	87/– HR		
			Mean diameter 29µm	128	87/– HR		
	AA2009/SiC/15p [2] Powder Metallurgy+extrusion	525°C-3h	T6 190°C	3	83/ – HR	0.5	(2)

	Material & Processing	Solution treatment	Precipitation heat treatment	*tpHc (h)*	*Hv/H0*	*R*	Com ments
	2014						
PRM	AA2014/Al_2O_3/10-15p [3] Mean Size 10µm Casting+extrusion	540°C-1.5h	T6 200°C	1.7	190/170	0.25	(3)
PRM	AA2014/ Al_2O_3/10-15 [4]		T6-200°C				
			10%Vf	2.5		0.3	
			15%Vf	1.7		0.2	
PRM	AA201/SiC/9-27p[5] Mean Size :24, 63 or 142µm Powder Metallurgy	510°C-0.75h	T6-160°C				(4)
			9%Vf-24µm	20	85/85HR	1	
			9%Vf-63µm	20	85/85HR	1	
			9%Vf-142µm	20	85/85HR	1	
			18%Vf-24µm	20	63/85HR	1	
			18%Vf-63µm	3	75/85HR	0.15	
			18%Vf-142µm	40	85/85HR	1.3	
			27%Vf-24µm	>20	65/85HR	>1	
			27%Vf-63µm	>20	65/85HR	>1	
			27%Vf-142µm	>20	65/85HR	>1	
PRM	AA2014/SiC/?p [6] Casting+extrusion	495°C-2h	T6				
			150°C	10.5	130/122	0.9	
			165°C	7.5	125/118	0.7	
			180°C	6	110/108	0.6	
			195°C	2.5	97/103	0.3	
PRM	AA2014/SiC/?p [7] Mean Size : 23µm Powder Metallurgy+extrusion	.490°C-0.5h	T6 160°C	12	165/	0.6	
SFRM	AA2014/Al_20_3/20f [8] Saffil Low pressure infiltration	510°C-2h	T6 180°C	24	175/130	1.1	
SFRM	AA2014/Al_20_3/20f [8] Saffil Low pressure infiltration	510°C-2h	T4	18	185/90	1	
PRM	**AA2024 – AA2124**						
PRM	AA2024/SiC/5-20p [9] Mean Size 14µm Casting+HIP+rolling	500°C-1.5h	T6-190°C				(5)
			5%Vf	9	162/145	0.82	
			10%Vf	8.3	167/145	0.75	
			15%Vf	7	172/145	0.65	
			20%Vf	6	184/145	0.55	
PRM	AA2024/SiC/5-20p [10] Mean Size : 40-100mm Stir-Casting	500°C-2h	T6-170°C				
			5%Vf	15	125/122	0.88	
			10%Vf	13	125/122	0.75	

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			20%Vf	9	125/122	0.53	
	AA2124/SiC/17.9 [11]p Mean Size 2.4µm Powder Metallurgy+hot rolling		T6 190°C	2.5	160/145	0.3	
	AA2124/SiC/17.9p[12] Mean Size 3-5µm Powder Metallurgy+extrusion	505°C-2h	T6				
			110°C	500	180/----		
			130°C	230	180/145	0.14	
			150°C	25	170/140	0.07	
			170°C	5	162/137	0.07	
			190°C	1	160/137	0.13	
			210°C	0.5	155/129	0.25	

	Material & Processing	**Solution treatment**	**Precipitation heat treatment**	***tpHc (h)***	***Hv/H0***	***R***	**Com ments**
	AA2024 – AA2124						
PRM	AA2124/SiC/17.9p[12] Mean Size 3-5µm Powder Metallurgy+extrusion	505°C-2h	T3-1.5% permanent strecht				
			110°C	1000	195/----		
			130°C	300	192/145	0.19	
			150°C	30	191/140	0.08	
			170°C	8	189/137	0.12	
			190°C	1.7	180/137	0.21	
			210°C	0.8	166/129	0.44	
	AA2124/SiC/17.9p[13] Mean Size 3-5µm Powder Metallurgy+extrusion	505°C-2h	T6-170°C-study of quench sensitivity				
			$500Ks^{-1}$	5	166/137	0.07	
			$82Ks^{-1}$	5	162/132		
			$1.6Ks^{-1}$	5	127/117		
			$0.15Ks^{-1}$	10	105/80		
			$0.07Ks^{-1}$	10	102/68		
	AA2124/SiC/17.9p [14] Mean Size : 3 µm Powder Metallurgy + HIP + forging	505°C-0.5h	T4	145	400/300 YS (Mpa)	1	
SFRM	AA2024/SiC/13.2w [15] Diameter0.5µm, Length 50µm Powder Metallurgy+extrusion	504°C-4h	T6 177°C	4	107/103	0.36	
	AA2024/Al_2O_3/9-14f[16] Saffil Squeeze-casting	500°C-3h	T6-190°C				
			9%Vf	8	125/155	1	
			14%Vf	8	120/155	1	

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Comments

(1) Decreasing the particle size eliminates the formation of GPB I zones and promotes the direct formation of GPB II zones. The time required for peak ageing is a function of the reinforcement size, and the hardening kinetics are different according to the size of particles. Three stages are observed for materials reinforced by 13 or 29µm particles, only two for the composite reinforced with the smaller 4µm particles.

(2) Studies on a modified 2009 alloy (with Ag addition) [2] show that the precipitation of the ? phase is suppressed in the composite and that the germination of S'phase is more homogeneous.

(3) The effect of solutionizing time (ST) at 540°C on the age hardening response of the AA2014/Al_2O_3/10-15p composites has been compared with the characteristics exhibited by the unreinforced alloy. Increasing the ST decreases the time required to get the peak hardness in the monolith (TPHm). In the composite the values of the TPHm at an ageing temperature of 200°C first decrease and then increase with an increase of ST.

(4) Low particle size does not affect the ageing behaviour. A high volume fraction of reinforcement leads to a loss of hardening due to the suppression of the GP zone formation.

(5) MMCs exhibit an accelerated ageing compared to the unreinforced alloys. The relation between time to peak hardness and SiC volume fraction V_f is : $t_{(minutes)}=606-1260V_f$

(6) DSC studies [9,12,17] generally show that the transformations involved in the precipitation sequence occur in a lower temperature domain. The peak temperature of S' precipitation was found to decrease with increasing volume fraction according to the function [9]: $T_{(S')}$ (°C) = 288.1-61.2 V_f

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AA 6061
1.0Mg-0.6Si-0.3Cu-0.2Cr

UNREINFORCED MATRIX

Precipitation sequence (schematic**)**

Vacancy-rich clusters → β"needle-shaped coherent precipitates →β' rod-shaped semi-coherent precipitates→ β Mg_2Si plate-shaped equilibrium precipitates

Thermal treatments

Solution treatment	530°C-1 to 2 hours	
Precipitation heat treatment	T6	175°C - 8 hours or 160°C – 18 hours

COMPOSITES

	Material & Processing	Solution treatment	Precipitation heat treatment	*tpHc (h)*	*Hv/H0*	*R*	Com ments
SFRM	AA6061/Al_2O_3/20f [1] Saffil 0.1mm Pressure infiltration	550°C-1h	T6 178°C	6	150/130	0.4	
	AA6061/Al_2O_3/10f [26] Saffil Length : 0.1mm, Diameter : 5µm Pressure infiltration	550°C-1h	T6 178°C	8.5	145/125	0.63	
	Rheocasting			10	134/120	0.75	
	AA6061/SiC/10f [26] Nicalon Length : 1mm, Diameter : 15µm Pressure infiltration	550°C-1h	T6 178°C	8.5	142/125	0.63	
	Rheocasting			8.5	142/125	0.63	
PRM	AA6061/Al_2O_3/10-15p [2] Mean size 12.5µm Duralcan process	540°C-1h	T6-200°C				
			10%Vf	0.66	950/820 (Mpa)	0.62	
			15%Vf	0.42	950/820 (Mpa)	0.38	
	AA6061/Al_2O_3/10p [3] Mean diameter 12µm	560°C-1.5h	T6 160°C				(1)
	Cast+extruded			>100	280/--- YS(Mpa)		
	Cast+extruded+rolled (500°C)			10	350/--- YS(Mpa)		

	AA6061/Al_2O_3/15p [4] Mean size 15µm **Casting+extrusion**	Heating up to 530°C at 2.78°C/min+15 min at 530°C	**T6** 150°C	43	137/110	1	
	AA6061/Al_2O_3/20p [5] Mean diameter 20µm **Powder Metallurgy+extrusion**	530°C-1.5h	**Quenched ,naturally aged 24 hours, artificially aged at 175°C**	8	127/----		
	AA6061/Al_2O_3/20p [6] Mean diameter 20µm **Cast+extrusion**	530°C-1.5h	**T6** 175°C	8	360/315 **YS**(Mpa)	1	(2)
	AA6061/Al_2O_3/20p [7] Mean diameter 20µm **Cast+extrusion**	530°C-1.5h	**T6** 175°C	8	138/122	0.73	(3)

	Material & Processing		**Solution treatment**	**Precipitation heat treatment**	***tpHc (h)***	***Hv/H0***	***R***	**Comments**
PRM	AA6061/SiC/10p [8] Mean size 15µm Compocasting+extrusion		520°C-2h	T6				(4)
				175°C	12		1	
				200°C	3.3		1	
				220°C	0.5	102/90	0.6	
	AA6061/SiC/8.6-13p [9] Mean size 54µm Stir casting+extrusion		520°C-1h	T6-177°C				
				8.6%Vf	6	112/93	0.75	
				13%Vf	2.5	120/93	0.31	
	AA6061/SiC/17.5p [10] Mean size 40µm Stir casting+extrusion		540°C-2h	T6 175°C	3	122/120	0.5	(5)
	AA6061/SiC/50p [11]		557°C-2h	T6-160°C				
	Mean size	85?µm			5	280/---		
		30?µm			5	305/---		
		14?µm			3	315/---		
	Squeeze-casting							
SFRM	AA6061/SiC /15w [12] Mean diameter 1µm Aspect ratio 20-50	Powd. Metall. + extrusion at Te Te	520°C-1.5h	T6 146°C				
		300°C			26	145/130	0.46	
		359°C			24.5	150/130	0.44	
		498°C			14.5	158/130	0.26	

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	AA6061/SiC/20w [4] Mean diameter 1µm Casting+extrusion	Heating up to 530°C at 2.78°C/min+15 min at 530°C	T6 150°C	18	148/110	0.42	
	AA6061/SiC/17w [13] Mean diameter 1µm Casting+extrusion	529°C-2h	T6 180°C	2-3	1500/1100 HB (Mpa)	0.4-0.6	
	AA6061/SiC/20w[14] F-9 Powder Metallurgy+extrusion	525°C-1h	T6 175°C	1.4	85/60 R_b	0.35	
PRM	AA6061/TiB_2/3.4-6.8p [15] Mean size 1µm In situ process+extrusion	560°C-1h	T6-250°C°				
			3.4% TiB_2	0.66	125/103	0.4	
			6.8% TiB_2	0.5	140/103	0.3	
	AA6061/B_4C/15p [16] Mean size 15µm Powder Metallurgy+extrusion	550°C-2h	T6 160°C	10	135/125	0.6	
	AA6061/B_4C/23p [17] Mean size 5µm Powder Metallurgy+extrusion	550°C-2h	T6 177°C	3	85/62 HR	0.3	

Natural Ageing or Low Temperature Precipitation Heat treatment

	Material & Processing	Solution treatment	Thermal treatment	t_{MHc} (h)	*Hv/H0*	*R*	Comments
SFRM	AA6061/Al_2O_3/20f [1] Saffil Pressure infiltration	550°C-1h	T6 140°C	>34	150/125	<0.1	
	AA6061/Al_2O_3/26f [19] Saffil Pressure infiltration	529°C-1h	T6-140°C	30	135/85	1	(7)
	AA6061/Al_2O_3/20f [19] Saffil Pressure infiltration	529°C-1h	T4		60/80		(7)
	AA6061/Al_2O_3/10f [26] Saffil Length : 0.1mm, Diameter : 5µm Pressure infiltration	550°C-1h	T6 140°C	92	160/---		
	Rheocasting			92	150/---		

Volume 2

	AA6061/SiC/10f [26] Nicalon Length : 1mm, Diameter : 15µm Pressure infiltration	550°C-1h	T6 140°C	100	140/---		
	Rheocasting			100	135/---		
	AA6061/SiC/10p [8] Mean size 15µm Compocasting+extrusion	520°C-2h	T6 145°C	25	137/110	1	(8)
	AA6061/SiC/14p [21] Mean size 15µm Powder Metallurgy+extrusion	529°C-2h	T4	2200	1100/800 HB (Mpa)	1	
	AA6061/SiC/17.5w[22] Length : 4 to 20 µm Squeeze-casting	529°C-2h	T4	2160	1300/800 HB (Mpa)		(9)
		557°C-2h		2160	1300/800 HB (Mpa)		
	AA6061/SiC/20w[14] F-9 Powder Metallurgy+extrusion	525°C-1h	T6 125°C	512	80/65 HR	2	

Comments

(1) Times given correspond to peak yield strength. Improvement of the homogeneity of the particle distribution by rolling results in further acceleration of the composite ageing response.
(2) Experiment are done with the same material as [7]. The lack of any significant acceleration in the aging behaviour in the composite (R=1) is attributed to the slight effect of spherical particles (R close to 1 in [7]), and to the experimental procedure using 0.2% flow stress rather than hardness.

(3) Comparative studies [18] between this AA6061/Al_2O_3/20p composite containing spherical alumina particles and a AA6061/Al_2O_3/15p composite containing angular alumina particles show that the two materials have an identical ageing behaviour.
(4) Composites and unreinforced matrices reach their peak harness at the same time if the ageing temperature is below 200°C. No difference is observed between the age-hardening behaviour of 6061/Al_2O_3/10p and 6061/SiC/10p (particles of the same mean size).
(5) Addition of 1.2wt%Fe in the AA6061/SiC/20p composite does not alter the kinetics of aging but significantly decreases the peak hardness value.
(6) Literature data on the effect of the introduction of a ceramic reinforcement in a 6061 alloy on the kinetics of zone formation during natural ageing or artificial ageing at low temperature are very different. They conclude either to the suppression of zone formation [19,23-24], to an acceleration or a suppression depending on the volume fraction of reinforcement [2], to a deceleration [14,22], or to no effect [19,22-25]. It seems in fact that the results are strongly affected by the elaboration conditions which may modify the composition of the alloy, and that defects introduced by the reinforcement have only a very slight effect on the precipitation

kinetics [24].
(7) The age-hardening characteristics of the alloy 6061 are considerably altered by the presence of fibers. Fibre array inhibits natural ageing.
(9) The effect of the reinforcement on the precipitation kinetics depends on the solution temperature. A deceleration of precipitation is observed for a solution treatment at 529°C, while no effect is observed for a solution temperature of 557°C. The hardness values corresponding to a solution treatment at 529°C do not correspond to a plateau (a permanent increase of hardness is observed up to an ageing time of 2160hours)

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AA 7XXX

UNREINFORCED MATRIX

Precipitation sequence

GPI zones→ GPII zones→ semi-coherent transition phase η' → η phase ($MgZn_2$)→ T phase ($(Al,Zn)_{48}Mg_{32}$)

Composition and Thermal treatments

Alloy	Composition	Solution treatment	Annealing	Precipitation heat Treatment
7020	Al-4.5Zn-1Mg			
7075	Al-5.6Zn-2.5Mg-1.6Cu-0.23Cr	465 to 480 °C	415°C	T6-120°C T7 (two stage): 107°C followed by 163 to 177°C
7091	Al-6.5Zn-2.5Mg-1.5Cu-0.4Co			
7475	Al-5.7Zn-2.3Mg-1.5Cu-0.22Cr	515°C preceded by soak at 465 to 477°C	415°C	120 to 175°C.
CW67	Al-9Zn-2.5Mg-1.5Cu-0.14Zr	475°C		T6 160 to 240°C

COMPOSITES

	Material & Processing	Solution treatment	Precipitation heat treatment	*tpHc (h)*	*Hv/H0*	*R*	Comments
PRM	**7020**						
	AA7020/SiC/5-10p [1] Mean Diameter : 70µm Stir-casting	540°C-10h	T6 –170°C				
			5% SiC	18	118/85	0.7	
			10%SiC	15	125/85	0.6	
	AA7020/SiC/5-10p [1] Mean Diameter : 70µm Stir-casting	540°C-10h	T8-10%plastic strain-170°C				
			5% SiC	17	118/89	0.8	
			10%SiC	13	125/89	0.6	
	AA7020/SiC/5-10p [1] Mean Diameter : 70µm Stir-casting	540°C-10h	T8-30%plastic strain-170°C				
			5% SiC	12	115/94	0.8	

			10%SiC	10	115/94	0.65	
	AA7020/SiC/5-10p [1] Mean Diameter : 70µm Stir-casting	540°C-10h	Quenched, Naturally aged. 10%plastic strain before artificial ageing at 170°C				
			5% SiC	10	107/105	0.83	
			10%SiC	9	113/105	0.75	
	AA7020/SiC/5-10p [1] Mean Diameter : 70µm Stir-casting	540°C-10h	Quenched, Naturally aged.30%plastic strain before artificial ageing at 170°C				
			5% SiC	7	101/---	0.87	
			10%SiC	6	101/---	0.75	

	Material & Processing	Solution treatment	Precipitation heat treatment	*tpHc (h)*	*Hv/H0*	*R*	Com ments
P R M	**7075**						
	AA7075/TiC//7.7p [2] Semi-solid particle incorporation +squeeze casting	480°C-1h	T6 160°C	8	131/142	2	(1)
	AA7075/SiC/5-40p [3] Mean Diameter : 44µm Powder Metallurgy+extrusion	470°C-1h	T6 80°C-120°C-200°C				(2)
	AA7075/SiC/5-10p [4] Mean Diameter : 10µm Semi-solid casting	460°C-40 min.	T6 140°C				(3)
	7091						
	AA7091/SiC/10-30p [5] Powder Metallurgy+extrusion	495°C-3.5h					(4)
	Others						
	CW67 (Al-9Zn-2.5Mg-1.5Cu-0.13Zr)/SiC/10-20p [6] Mean Diameter : 5-8µm Powder Metallurgy+extrusion	475°C-1.5h					(5)

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	CW67/SiC/10-25p [7-8] Mean Diameter : 5µm Powder Metallurgy+extrusion		T6 120°C	6	210/190	0.5	(6)
	Al-7Zn-2Mg-2Cu/SiC/20p [9-11] Mean Diameter : 5µm or 16µm Powder Metallurgy+extrusion	510°C-4h	T6 120°C-	24	520/520 YS (Mpa)	1	(7)
	Al-7.5Zn-1.5Mg/Al_2O_3/1-5p [12] Mean Diameter : 0.3µm Melt casting	450°C	T6 150°C	2	104/65 HR	0,8	

Comments:

(1) TiC particles do not accelerate ageing at 120°C, buy retard it at 160°C. The presence of TiC particles decreases the GP zone volume fraction and increases the amount of η' precipitates formed.

(2) In the low volume percentage (5,10) hardness-ageing curves are similar to those of the unreinforced alloy, but hardening is weaker than in the unreinforced alloy. In the high volume percentage (20, 30, 40) no hardening is observed, but rather softening.

(3) A slight acceleration of the precipitation process seems to be due to the presence of the reinforcement.

(4) DSC studies show that, increasing the SiCp concentration was found to decrease the temperatures at which GPI and GPII zones precipitate at their maximum rates and to increase the temperature at which GPI zones revert. The formation kinetics of the transition phase η' and of the equilibrium phase η were not modified by the presence of the reinforcement.

(5) DSC studies show that there is an acceleration of nucleation and growth of precipitates in CW67/SiC/20p but that there is only an acceleration of growth in CW67/SiC/10p.

(6) Ageing kinetics of composites at 120°C are identical to that of the unreinforced matrix up to a reinforcement volume fraction of 10%. Materials containing more than 15% reinforcement follow a different sequence.

(7) Yield stress at peak ageing for the unreinforced matrix and the composite are equivalent. Ageing deceleration is observed in overaged states. Depletion of Mg atoms, due to the interaction with SiO_2 at the surface of particles, and the lack of interaction of Zn atoms with dislocations seem to be responsible for this deceleration.

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AA 8090
2.3 Li-1.3Cu-1Mg

UNREINFORCED MATRIX

Precipitation sequence
Two precipitation sequences occur in the 8090 alloy [1]
i) δ’coherent Al_3Li → δ equilibrium AlLi
ii) GPB zones→ semi-coherent S’→ incoherent equilibrium S (Al_2CuMg)
Thermal treatment
Solution treatment :T=530°C   Precipitation heat treatment : T6, T=190°C-12h

COMPOSITES

	Material & Processing	**Solution treatment**	**Precipitation heat treatment**	***tpHc (h)***	***Hv/H0***	***R***	**Comments**
	AA8090/SiC/20p [2] Mean diameter :3µm Powder Metallurgy	Composite : 560°C Unreinforced alloy : :530°C	T6 170°C	6	160/150	0.1	
	AA8090/SiC/17p [3] Mean diameter :3µm Powder Metallurgy (3 different processes)	530°C-0.5h	T6 170°C	10	340/320 YS (Mpa)	1	(1)
	AA8090/SiC/17p [5] Mean diameter :3µm Powder Metallurgy	530°C-2h	T6 170°C	4 (t_MHc)	195/155	0.4	(2)
***P* R M**	AA8090/SiCp/15 [6] Spray casting	540°C	T6				
			130°C	37	96/83	0.75	
			150°C	12	112/90	0.6	
			175°C	10	80/79	0.5	
			190°C	6	107/102	0.4	
	AA8090/SiCp/15 [6] Spray casting	540°C	T8- 2% plastic strain				
			130°C	11.5	107/110	0.5	
			150°C	10	102/105	0.5	
			170°C	10	112/110	0.4	
			190°C	6	96/104	0.5	

Comments:
(1) Different PM processes lead to different kinetics of age hardening of the composite
(2) Hardness variation with ageing time exhibits a plateau
(3) Solution treatments of Al-Li alloys and composites may lead to a significant loss of lithium in the surface layers [4]

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CASTING ALLOYS

UNREINFORCED MATRIX

General schematic precipitation sequence

Vacancy-rich clusters → β''needle-shaped coherent precipitates → β' rod-shaped semi-coherent precipitates→ β Mg_2Si plate-shaped equilibrium precipitates

Composition and thermal treatments

Alloy	Composition	Solution treatment	Precipitation heat treatment
356	Al-7Si-0.35Mg	535-540°C 12h	T6-150-155°C 2 to 5h
357	Al-7Si-0.5Mg	535-540°C 12h	T6-175°C.-6h 155°C-12h
359	Al-9.5Si-0.5Mg	540°C 10-14h	
336	Al-12Si-2.5Ni-1Mg-1Cu	515°C 8h	205°C 7 to 9h

COMPOSITES

	Material & Processing	Solution treatment	Thermal treatment	*tpHc (h)*	*Hv/H0*	*R*	Com ments
	A356						
P R M	A356/Glass/5-10p[1] Mean Diameter : 45µm Stir-casting	540°C	T4				
			5% Glass	125	115/105	0.9	
			10% Glass	100	120/105	0.7	
	A356/Glass/5-10p[1] Mean Diameter : 45µm Stir-casting	540°C	T6-170°C				
			5% Glass	12	148/140	0.75	
			10% Glass	9	155/140	0.55	
	A356/Glass/5-10p[1] Mean Diameter : 45µm Stir-casting	540°C	T8-15% compression-170°C				
			5% Glass	6	146/140	0.67	
			10% Glass	3.5	154/140	0.4	
	A356.2/Fly ash/5wt%p [2] Median Size 65µm Stir casting	538°C-3h	Quenched in hot water 80°C Aged 155°C	28	92/92 (HR)	1	(1)
			As-cast		60/56 (HR)		
	A356/SiC/15p[3] Mean Size : 15µm Duralcan Process	535°C-6h	Quenched in hot water 80°C Aged 200°C	5	105		
	A356/SiC/10-20p[4] Mean Size : 15µm Squeeze-casting	520°C-8h	T6-160°C			5	(2)
			10%SiC	20	125/120		
			20%SiC	20	145/120		
	A356/SiC/10-20p[4] Mean Size : 15µm Squeeze-casting	520°C-8h	T6 Naturally aged 24h-Ageing 16 0°C			1	(2)
			10%SiC	20	120/110		
			20%SiC	20	130/110		

	Material & Processing	Solution treatment	Thermal treatment	*tpHc (h)*	*Hv/H0*	*R*	Com ments
P R M	**A357**						
	A357/SiC/15p[5] Mean Size : 20µm Squeeze casting	525°C-24h	T6 170°C	8	153/124	1	(3)

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	A357/SiC/15p[5] Mean Size : 20µm Squeeze casting	525°C-24h	T6 Naturally aged 24h-Ageing 170°C	24	157/126	1	(3)
	A359						
	A359/Al_2O_3/10p[6] Mean Size : 20µm Stir casting	540°C-8h	Quenched in warm water 60°C Ageing 155°C	24	325/304 YS (MPa)	1	
	A359/SiC/10p[6] Mean Size : 20µm Stir casting	540°C-8h	Quenched in warm water 60°C Ageing 155°C	24	336/304 YS (MPa)	1	
SFRM	A336						
	A336/47%Al_2O_3-53%SiO_2/10-25f[7] Length 10µm, Diameter 2µm Squeeze casting	520°C-9h	Quenched in warm water 80°C Ageing 205°C				
			10% fiber	4	118/115	1	
			15% fiber	4	120/115	1	
			20% fiber	3.5	125/115	0.9	
			25% fiber	3	130/115	0.75	
	Others						
	AlSi7Mg0.6/SiC/10f[8] Length 3-6mm, Diameter 10-15µm Rheocasting	540°C-8h	T6 180°C	1	94/82	0.04	
	AlSi12CuMgNi/ Al_2O_3-SiO_2/20f [9] Saffil (96%Al_2O_3-4%SiO_2) or Fiberfrax (50%Al_2O_3-50%SiO_2) Squeeze-casting		Natural ageing 100h Ageing 200°C				(4)
			Saffil		176/124	0.5	
			Fiberfrax		131/124		

Comments

(1) The incorporation of fly ash in the A356.2 matrix significantly improves the hardness of as-cast products ,but does not modify the ageing response of the material.

(2) A two-step ageing process results in comparable ageing conditions.

(3) No isothermal study of the evolution of hardness of the monolithic alloy and of the composite. The thermal treatments for the two materials are identical.

(4) The hardness of the homogeneised quenched and room temperature pre-aged samples was 94 HV 158 HV and 131HV for the unreinforced, the Saffil-reinforced and the Fiberfrax-reinforced alloys respectively. The Fiberfrax composite shows no hardening at all due to the chemical reaction between the reinforcement and the matrix.

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Volume 2

Mg-BASED MATRIX

COMPOSITES

	Material & Processing	**Solution treatment**	**Thermal treatment**	***tmHc/* tmHm *(h)***	***Hv/H0***		**Comments**
PRM	AZ80A/B_4C/28p [1] Mean Size Powder Metallurgy	Rapid heating to 260°C + heating to 405°C at 70°C/hour +15h at 405°C	T6 177°C	30/60	1300/850 HR (Mpa)		
PRM	**Material & Processing**	**Solution treatment**	**Thermal treatment**	***tpHc/ (h)***	***Hv/H0***	***R***	**Comments**
PRM	MgZn6/SiC/20p [5] Mean Size : 8-10µm Casting	330°C-1h	T6				
			100°C	500	70HR		
			125°C	300	62HR		
			150°C	100	63HR		
			175°C	20	63HR		
			200°C	5	60HR		
PRM	Mg-9Al-1Zn/SiCp [3]	475°C-15h	Artificial ageing 170°C	32.5	170/100	1	
SFRM	ZA-27/Glass1-/5f [2] Mean diameter :4-6µm Mean Length:400-600µm Compocasting		Artificial ageing-125°C				
			1%Vf	12	135/135	0.75	
			3%Vf	12	138/135	0.75	
			5%Vf	12	140/135	0.75	
HYBRID	ZK60/ SiC-B_4C/12w-12p[4] W : Diameter:0.5-1.5µm Length : 10-50µm P : Mean Size : 7µm Pressure Infiltration + extrusion	400°C- 4h	T6 170°C	4	130/70	0.1	

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