RECENT ADVANCES IN THE TECHNOLOGY OF ALUMINIUM-MAGNESIUM ALLOYS

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ALLOYS of aluminium with copper, to which small amounts of manganese, magnesium and silicon are added, belong to the well known group of alloys termed "Duralumin", and were amongst the earliest of aluminium alloys to be used commercially on account of their age-hardening characteristics.

Alloys of aluminium with magnesium as the principal alloying element, first attracted the interest of investigators as early as 1900, and since then, cast alloys containing as much as 10% magnesium have been used for specified purposes. During recent years, binary alloys of aluminium with magnesium have been extensively and increasingly used in several applications requiring light weight, coupled with high-strength, good corrosion resistance, high temperature mechanical properties, and good wear resistance. As for example, over 1,000 tons of the wrought aluminium-magnesium alloy N5/6, (3·5–5·5% magnesium), have been used for super-structures in each of the 40,000-tons Ocean liners "Oriana" and "Canberra" recently completed in the United Kingdom[1] (Table I). Alloys of aluminium and magnesium have also been considered[2] suitable for structural purposes in the fabrication of high speed aircrafts in view of their ability to stand thermal stresses as influenced by non-uniform heating, thermal conductivity, expansion, elasticity and density. Alloys containing 2·5, 3, 4 and 5% Mg have been shown to be more corrosion resistant than steel when used in condensation cooling equipment for cracking plants in environments containing low concentrations of H_2S and CO_2.

In India, the production capacity of aluminium is being stepped up from the present 17,000 tons per annum to about 83,000 tons per annum by 1965–66. Schemes for the production of air-craft including high speed aircraft, within the country have reached an advanced stage, according to newspaper reports. The country has large reserves of magnesium ores and processes have been developed at the National Metallurgical Laboratory for the production of magnesium metal of high purity from these ores. The production of magnesium metal within the country, however, does not figure in the projects to be taken up during the Third Five Year Plan period. This is a serious omission and needs to be rectified.

In the context of these developments, the production of magnesium and the development of aluminium-magnesium alloys, particularly to replace certain imported alloys of the "duralumin" type, assume considerable importance. The present paper attempts to review the existing state of knowledge of the various aspects of the production and properties of aluminium-magnesium alloys.

Alloys of aluminium with magnesium, which are commonly used in either cast or wrought condition and are covered by B.S.S. or A.S.T.M. specifications are given in Table I along with their distinctive characteristics. Physical and mechanical properties of a few known cast binary aluminium-magnesium alloys are summarised in Table II. In general, aluminium-magnesium alloys are characterised by high strength, excellent corrosion resistance and good machinability. The density and electrical and thermal conductivities of these alloys decrease with an increase in magnesium content.

The tensile strength of alumium-magnesium alloy castings increases with magnesium content till about 6%, after which it begins to decrease; ductility of these alloys also shows a sharp decline above about 6% Mg, whereas hardness continues to rise with the magnesium content (Fig. 1). The variation in solid solubility of magnesium in aluminium from about 15% at the eutectic temperature (451°C) to less than 4% at room temperature renders some of the alloys susceptible to improvement in tensile properties, particularly the alloys containing more than 6% magnesium. It may be noted, for example, that the elongation of Al–10% Mg alloy, which is only about 0·5% in the as cast condition, rises to about 14% after solution heat-treatment and the tensile strength increases from 25,000 lb/sq in to about 44,000 lb/sq in. The increase in both strength and ductility has been ascribed by

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TABLE I

Common casting and wrought aluminium-magnesium alloys.

Sl. No.	A.S.T.M. or Al. Assocn. designation	B.S.S. designation	Nominal composition	Mechanical properties				Outstanding characteristics	Typical uses
				U.T.S. p.s.i.	Elongation in 2″ g.l.	Fatigue strength p.s.i.	Brinnel hardness		
A—Casting alloys									
1.	G4A	LM5	4% Mg	25,000 (C)	9·0	5,500	50	Excellent resistance to corrosion and tarnish.	Dairy and food handling equipment, cooking utensils, chemical fittings, hardware, etc.
2.	G8A	—	8% Mg	45,000 (C)	8·0	23,000	—	Excellent resistance to corrosion and tarnish, excellent strength and ductility.	Aircraft fittings, wheel-flanges and brake-shoes, marine fittings, hardware, outboard motor brackets.
3.	G10A	LM10	10% Mg	46,000 (W)	14·0	7,000	75	Highest strength of aluminium sand casting alloys, excellent machineability and corrosion resistance.	Refrigerator fittings carburator bodies, thin section general purpose castings.
4.	GS42A	—	4% Mg, 1·8% Si	20,000 (C)	2·0	—	50	Good corrosion resistance.	Pipe fittings for marine and general use, cooking utensils.
5.	GZ42A	—	4% Mg, 1·8% Zn	27,000 (C)	7·0	—	60	Good resistance to corrosion and tarnish.	Cooking utensils.
B—Wrought alloys									
6.	5,250	H10 H20 H30	0·4–1·5% Mg, 0·1–0·4% Cu, 0·4–0·8% Si, 0·7% Fe	24,600 (O) 40,300 (WP)	18 8	— 17,900	— 90–100	High work-hardening capacity, high strength, better formability and excellent corrosion resistance.	Trim mouldings, inside and outside panels for refrigerators, window frames, auto-trailors, kitchen cabinets, machinery parts, etc.
7.	5,086 5,083	N5/6	3·5–5·5% Mg, 0·6% Si, 0·7% Fe	38,000	12–18	23,000	70	High strength, and corrosion resistance, excellent weldability.	In sheet form and as structural members for marine vessels, truck and trailor bodies, chemical storage tanks.
8.	5,052	—	2·5% Mg, 0·25% Cr	29,000 (O)	30	18,000	45	High strength.	Pressure tubes and vessels, fan blades, tanks, fittings, aircraft engine, cylinder baffles.
9.	5,056	N6	4·5–5·5% Mg, 1·0% Mn, 0·7% Fe, 0·6% Si	31,500 (O)	18	18,700	55	High strength at elevated temperatures, good weldability.	Fuel tanks, structural uses, welded dump truck bodies.
10.	5,454		2·4–3·0% Mg, 0·5–1·0% Mn, 0·4% max Si+Fe	36,000 to 48,000	8–22	—	62–81	Maximum high temperature strength in Al-Mg alloys, resistant to high temperature corrosion and stress corrosion, welding grade alloys.	Structural applications for use at temperatures above 150°F, vessels, storage tanks, piping, etc. in chemical process in[illegible]

C=as cast
W=solution heat-treated temper
WP=precipitation heat-treated tempe
O=annealed.

TABLE II

Properties of some known cast aluminium-magnesium alloys.

Sl. No.	Property		Al-1·2 Mg	Al-3·8 Mg	Al-8 Mg	Al-10 Mg
1.	Tensile strength	75°F	21,000 (for 0) to 32,000 psi (for H38)	25,000 psi	42,000 psi	46,000 psi
		600°F	6,000 psi	9,000 psi		10,500 psi
2.	Yield strength	75°F	8,000 psi (for 0) to 29,000 psi (for H38)	12,000 psi	23,000 psi	25,000 psi
		600°F	4,000 psi	4,000 psi		3,500 psi
3.	Elongation %	75°F	24% (for 0) to 6% (for H38)	9%	7%	14% (W)
		600°F		17%		70%
4.	Modulus of elasticity		10,300,000 psi	10,300,000 psi	10,300,000 psi	10,300,000 psi
5.	Endurance limit (500,000,000 cycles)		12,000 psi to 14,000 psi	5,500 psi	18,000 psi	7,000 psi
6.	Modulus of rigidity		3,850,000 psi	3,850,000 psi	3,850,000 psi	3,850,000 psi
7.	Thermal expansion					
	20–100°C		0·0000237/°C	0·0000240/°C	—	0·0000245/°C
	20–200°C		0·0000246/°C	0·0000250/°C	—	0·0000255/°C
	20–300°C		0·0000255/°C	0·0000260/°C	—	0·0000265/°C
8.	Specific heat at 100°C		approx. 0·23 cal/g	approx. 0·23 cal/g	approx. 0·23 cal/g	approx. 0·23 cal/g
9.	Latent heat of fusion		approx. 93 cal/g	approx. 93 cal/g	approx. 93 cal/g	approx. 93 cal/g
10.	Thermal conductivity (25°C)		0·46 cal/cm^2/cm/°C/sec	0·33 cal/cm^2/cm/°C/sec	0·24 cal/cm^2/cm/°C/sec.	0·21 cal/cm^2/cm/°C/sec
11.	Density (25°C)		2·69g/cc (0·097 lbs/cu in)	2·65 g/cc (0·096 lb/cu in)	2·53 g/cc (0·091) lbs/cu in)	2·58 g/cc (0·093 lbs/cu in)
12.	Hardness		36 BHN (for 0) to 63 (for H38)	50 BHN	—	75 BHN
13.	Shear strength		15,000 psi (for 0) to 20,000 psi (for H38)	20,000 psi	—	33,000 psi

Temper designations 0=Annealed. H38=Strain hardened and stabilised (fully hardened).

Kato and Nakamura[5] to the dissolution on heat-treatment of more than 10% magnesium which remains in solid solution after quenching or air cooling.

Casting of aluminum-magnesium alloys, particularly those containing more than 5% magnesium presents special problems involving porosity due to metal-mould reaction and the tendency of the alloy to dross formation and to gas absorption. However, techniques have been developed by Whitaker[6] and by Cibula[7] which require (*i*) the use of pure materials, (*ii*) grain refinement, (*iii*) degassing and (*iv*) provision of properly designed feeding arrangements. It has been found by Jay and Cibula[8] that degassing uniformly distributes microporosity in high magnesium content alloys, resulting in higher mechanical strength. Lack of proper feeding and degassing resulted in the formation of layer porosity irrespective of magnesium content.

Alloys containing as much as 2–3% magnesium can be reduced from cast ingots by forging or rolling with little difficulty. When alloys contain more than about 3% magnesium, working of cast ingots becomes increasingly difficult. This condition has precluded the commercial development and application of wrought alloys containing more than about 6% magnesium.

In experimental aluminium-magnesium alloys prepared[9] from super-pure materials (which could be forged or extruded), the tensile strength increased with magnesium content up to 15% and showed a steep fall thereafter ; hardness and yield strength increased continuously with magnesium content, while elongation remained relatively constant at about 30% in the range 2–12% magnesium. At higher temperatures both tensile and yield strengths fell with rise in temperature of treatment, and elongation rose appreciably above 300°C. The endurance limit of these alloys shows an increase with Mg content up to 6%, above which the increase in fatigue resistance is much slower.

New alloys developed

The compositions and methods of production of commercial alloys developed in various countries are generally covered by patents, particularly when the alloys have been developed to obtain certain specific characteristics. The emphasis is generally

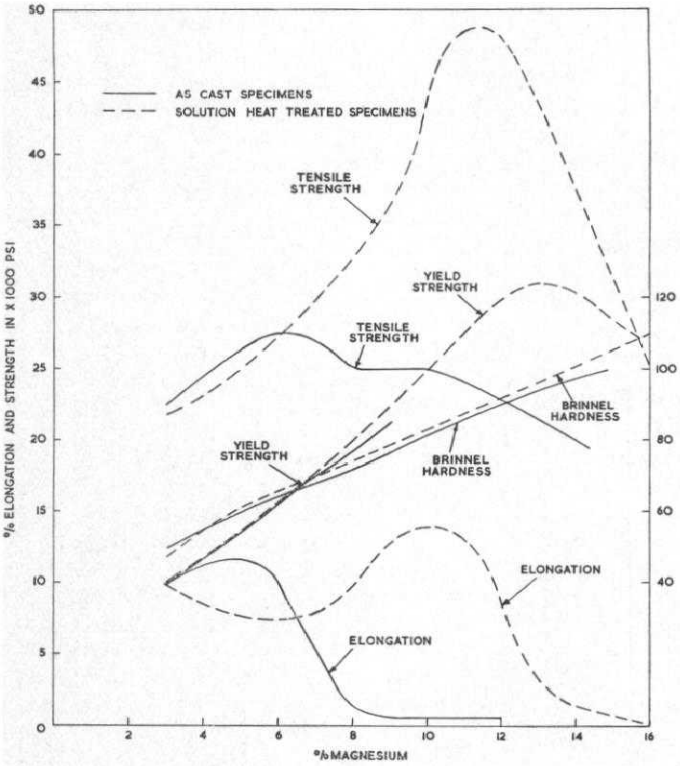

Fig. 1.

Effect of heat-treatment on the mechanical properties of cast Al-Mg alloys.

on getting improved mechanical properties by treatment with small quantities of refining agents.

Increased tensile strength, elastic limit and capacity for structural hardening are claimed by the addition of a critical amount of zinc, (e.g. 0·5–3% in cast 12% Mg alloys and 1% in those with 8% Mg)[10], provided the magnesium content does not exceed 14%. For obtaining maximum benefit from this addition, the alloys have to be homogenised in the absence of air and/or steam, in an inert atmosphere or in a fused salt bath. For example, a tensile strength of 70,000 lb/sq in, an elastic limit of 45,000 lb/sq in, an elongation of 6–8% and a brinnel hardness of 140, have been obtained in a cast alloy containing Mg–12%, Zn–2%, Mn–0·4%, Al balance, after suitable homogenisation, quenching and ageing treatment.

The beneficial effects of addition of zinc to aluminium-magnesium alloys have been utilised in the production of high strength alloys free from susceptibility to intercrystalline and stress corrosion, e.g. alloys containing 3·4–12% Mg, 2–6% Zn, 0·05 Ca and 0·01% Mn[11] and 7–9% Mg, 1·2–2·5% Zn, 0·1–0·2% Cu[12], have recently been produced which claim these characteristics; the latter alloy attains a tensile strength of 42,000 psi, yield strength of 25,000 psi, after the casting is solution heat-treated at 440–505°C and quenched in water at 80–100°C.

A new alloy–5657 (1–1·5% Mg) has been produced by Reynolds Metal Co.[13], which is claimed to have 15% better reflectivity than any aluminium alloy yet produced. This alloy is expected to find use in motor car and appliance industries.

The addition of chromium and manganese in small quantities has been observed to exercise favourable effects on the mechanical properties, weldability and corrosion resistance of aluminium-magnesium alloys[14]. Most useful additions recommended are 0·15–0·25% Cr and 0·30–0·45% Mn, in Al–3% Mg alloy and 0·1 to 0·15% Cr and 0·15–0·25% Mn in Al–5% Mg alloy. Increased purity of the base aluminium metal was found to improve corrosion resistance of the alloy but slightly increased the tendency to crack during working[15].

Presence of silicon is known to result in the lowering of mechanical properties, but the simultaneous addition of chromium and manganese to silicon containing aluminium-magnesium alloys was considered useful in improving these characteristics. A high strength aluminium-magnesium alloy, aluminium 5456 (Mg 5·25%, Mn 0·8%, Cr 0·1%), suitable for use in making portable emergency landing strips has been developed by Aluminium Corporation of America. This alloy successfully resists the hot jet blast and furnishing landings associated with jet aircraft[16].

The effect of addition of titanium, beryllium and boron to cast aluminium-magnesium alloys having 3–12% Mg, has been studied by several authors[17–19]. The additions are to be held within the limits, Be 0·001–0·2%, B 0·001–0·01% and Ti 0·05–0·25%. These alloying elements are claimed to cause grain refinement of the alloys leading to improvements in the tensile strength, yield strength and ductility. Also, addition of beryllium substantially reduces the loss of magnesium by oxidation in melts, and prevents the damaging effects (excessive porosity) of moisture in green sand moulds.

Ransley and Talbot[20] have shown that the presence of traces of sodium (of the order of $>$0·001%) in high magnesium ($\sim$5% Mg) aluminium-magnesium alloys severely impairs their hot working properties (Fig. 2). The embrittlement has been attributed to the presence of sodium in the elemental state, particularly when the magnesium content exceeds about 2%, and is considered to be due to the absorption of the elemental sodium on internal surfaces generated on plastic flow during hot working and consequent modification of growth of the grain boundary cavities (Fig. 3). The "free" sodium is supposed to be released due to a phase change involving a ternary Na–Al–Si compound and the dissolved magnesium, according to the equation: $(\mathrm{NaAlSi}) + 2\mathrm{Mg} \rightarrow \mathrm{Mg_2Si} + \mathrm{Al} + \mathrm{Na}$ "free".

Heat treatment

Heat treatment and age hardening of the alloys of aluminium-magnesium system have been adapted to suit the development of various desired characteristics. Processes containing some novel features have been patented. One of these processes[21] consists in quenching the material from the solution heat treatment temperature directly to the age hardening temperature

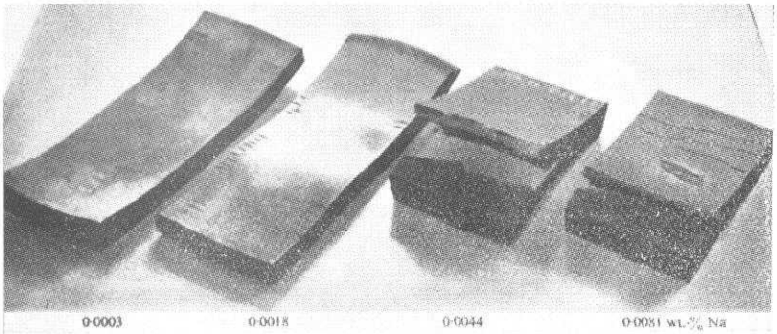

Fig. 2.
Progressive embrittlement effect of sodium content in Al-5% Mg alloy.
(after Ransley and Talbot[19])

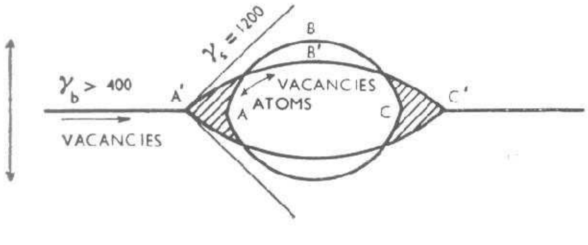

Fig. 3.
Pore shape developed under plastic flow conditions at elevated temperatures: (*a*) Ductile fracture; (*b*) brittle fracture associated with reduction in free surface energy by absorbed impurity.
(after Ransley and Talbot[19]).

(150-200°C). This prevents hardening of the alloy at temperatures below or above the desired temperature and results in the development of more uniform structures. In another process patented by Messrs. Westinghouse Electric Co.[22], the solution heat treated casting is cooled to –120°F (–84°C) for 4 hours. The process is claimed to be cheaper and more effective in ensuring dimensional stability of the heat treated casting during machining than is the usual stabilisation heat treatment, and the resulting castings can be machined with improved dimensional stability in one instead of the usual three stages.

The initial stages of the decomposition of supersaturated solid solutions during the heat treatment of aluminium base alloys including aluminium-magnesium alloys containing 1·4% Mg_2Si, has been studied by Buinov and coworkers[23–25], using the technique of electron-microscopy. The specimens were quenched from 540°C and aged at various temperatures, and oxide replicas obtained from electropolished specimens. It was observed that in high temperature ageing, the size of the individual grains became larger; the quantities of the various phases present, however, remained the same throughout. The recrystallisation curve of commercial aluminium-magnesium alloys, containing 1·5–5% Mg, and cold worked to different degrees was studied by Paganelli[26] using the X-ray diffraction technique. He found that for a given degree of cold working, the recrystallisation range (i.e. the temperature of commencement and completion of recrystallisation) was lowered as the magnesium content of the alloy was increased.

The effect of various ageing treatments (up to 400 days) both at room and elevated temperatures, on the mechanical properties of sand cast and solution heat treated test bars, was studied by Pollard[27]. He observed that at ageing temperature of 100-150°C the elongation and ultimate tensile strength increased and the yield strength decreased with ageing time. At room temperature, on the other hand, the yield strength and ultimate tensile strength increased and elongation decreased with time. He did not observe any significant change in these properties on ageing at 50 and 75°C even for as long as 400 days. Stubhington[28] studied the effect of heat-treatment on fine grained Al-7% Mg alloy specimens, which gave a steel type S-N curve. He observed that any type of heat treatment (ageing or solution treatment), resulted in producing typical S-N curve of aluminium alloys. This effect has been ascribed by him to an increase in the grain size of the specimens on heat treatment.

Cast aluminium-magnesium alloys with magnesium contents of 5% or above are sensitizable to intercrystalline corrosion, when heat treated or tempered at temperatures of 70-200°C. Saulnier[29] observed that such treatment resulted in the precipitation of minute particles of Al_3Mg_2 both in the grain boundaries and inside the grains. These particles are surrounded by matrix rings low in magnesium. When the Al_3Mg_2 grains exist in sufficient numbers at the grain boundaries (as would happen in the case of high magnesium alloys), low magnesium rings merge forming a practically continuous strip. When silicon was present as an impurity in the alloy, it passed into solution and later precipitated as Mg_2Si, causing structural hardening and sensitization to intercrystalline corrosion. Guilhaudis[30] has described the influence of various stabilising heat treatments capable of reducing the harmful effects of the low temperature heating of Al-5% Mg alloys and has recommended the methods of stabilising annealing, interrupted quenching and control of cooling rate for reducing the susceptibility of these alloys to intercrystalline corrosion.

Strength and reliability of the aluminium-magnesium alloys used in highly stressed products ranging from boat-hulls to ballistic missiles, have been increased by a new tempering process developed by Alcoa[31]. This process makes possible two new tempers H323 and H343 giving maximum resistance to stress corrosion for sheets in alloys 5456 (Mg 4·7 to 5·5%, Mn 0·5–1·0%) and 5083 (Mg 4 4·9%, Mn 0·5 1%). In both cases the tempering processes result in 4–10% increase in mechanical properties over the best obtainable hitherto.

Long exposures (as much as 4,000 hours) of aluminium-magnesium alloys at room temperature were found by Mori[32] to cause a decrease in their ultimate tensile strength and proof-stress, and an increase in elongation. This change was comparable with that produced by annealing for 5 hours at a temperature of 90-100°C, and depended on the magnesium content and degree of cold working given to the alloy. Variations observed in Al 99, Al 99·,5 Al 99·8 and Al 99·99% were very small. But in the case of alloy AM 30 the ultimate tensile strength and elongation were found to increase and the proof stress to decrease, as a result of long exposures at room temperatures.

Johnson[33] has observed that of all the low temperature construction materials, aluminium alloys, particularly those of the 5,000 series (i.e. aluminium-magnesium alloys with or without manganese) maintain high toughness and ductility even at temperatures as low as −250°C (−423°F). As the temperature decreases, the tensile strength of annealed alloys increases markedly, being 35 to 50% higher at −320°F (−196°C) than at room temperature. Similarly, they have higher tear resistance, and show ductile fractures which do not indicate any transition in fracture behaviour of these alloys on cooling. The alloys considered showed excellent resistance to stress corrosion, caused by the presence of a continuous grain boundary precipitate, which is anodic to the grain in the presence of an electrolyte.

Corrosion

Although most aluminium alloys are resistant to corrosion, considerable research work has been done on the extent and mechanism of corrosion in various alloys under different conditions of treatment.

Maltstev and coworkers[34] have studied the formation and structure of oxide films formed on liquid aluminium and its alloys using the electron diffraction technique. They found that films formed on pure molten aluminium at temperatures up to about 700°C were amorphous, and consisted of crystalline α–Al_2O_3 above this temperature. In the case of Al–Mg alloys, the oxide films formed consisted mainly of MgO, with Mg_3N_2 appearing when the alloy was exposed to air at high temperatures and/or for a longer time. The kinetics of oxidation and magnesium evaporation of Al–3% Mg alloys have been studied by Smeltzer[35] using an optical microscope. He found that the alloy was oxidation resistant up to 200°C. At temperatures above 350°C, the oxidation rate was initially inversely proportional to oxide-film thickness, which changed to a constant rate after prolonged exposures. Selective oxidation of magnesium caused formation of aluminium inclusions in the surface oxide layer. The surface oxide film formed was found to offer resistance to further oxidation of the alloy.

Polmear[36] observed that high temperature oxidation of aluminium-magnesium alloys in air, and in an atmosphere containing water vapour and sulphur compounds, resulted in the formation of cavities and blisters. These have been ascribed by him to the diffusion from the surface of atomic hydrogen which may be formed by the surface dissociation of water vapour. Sulphur compounds cause a breakdown of the oxide films because of their ability to form SO_3 easily by oxidation.

Intercrystalline corrosion of wrought aluminium-magnesium alloys, with varying magnesium contents, has been studied by Hugony and coworkers[37, 38]. They observed that susceptibilty to intercrystalline corrosion depended on the magnesium content and could be avoided by limiting it to 4·5%. They also found that the method of alloy fabrication, presence of other minor alloying elements, degree of work hardening and the heat treatment of the alloys, also, influenced the corrosion characteristics. Relationship between grain boundary structure and intercrystalline corrosion has been investigated on an Al–7% Mg alloy by Erdmann-Jesnitzer[39], using blackening of the grain boundaries as a measure of corrosion attack. He observed that the presence of minute particles of Al_3Mg_2 in the grain boundaries was a contributory cause of intercrystalline corrosion. Vance[40] has noted that the susceptibility of aluminium-magnesium alloys to cracking due to stress corrosion was directly related to the magnesium content of the alloy, being nil at 2·5% Mg and maximum at 8% Mg.

Physical properties

As has been mentioned previously, all aluminium alloys have been developed to satisfy certain requirements of physical properties, and most of the recent work on the subject has been referred to in earlier sections of this paper. Some more work dealing chiefly with the physical properties of aluminium-magnesium alloys is summarised in the following paragraphs.

Marsh, Maninger and Manning[41] investigated the plastic behaviour of binary aluminium-copper and aluminium-magnesium alloys using the internal friction method. They have shown that nominal additions of 0·1, 1·0 and 5·0% by weight of Cu and Mg to aluminium have significant effects on the damping behaviour of the alloys. Small additions raise the internal friction and lower the shear modulus above 200°C. Large additions of the metals have the opposite effect. Ageing decreased the internal friction in most cases. Internal friction also decreased with a rise of temperature ; for alloys richer in these metals, the effect is reversed. Internal friction of recrystallised solid solution of aluminium-magnesium containing 0·01, 0·05, 1 and 2% Mg by weight was studied by Grin[42] who observed the presence of a single maximum value near 300°C for all the alloys, except the ones containing 0·05 and 1% Mg in which cases a second maximum was observed at 380°C. The appearance of the second maximum has been attributed to the relaxation of stress at the boundaries of mosaic blocks.

The behaviour of an Al-2% Mg-Mn alloy during extrusion and subsequent cold working has been studied by X-ray and microscopic examination by Rosenkrauz[43]. His work suggests that, in the extruded sections, zones super-saturated in manganese are formed in the direction in which grain growth is possible presumably as a result of rapid solidification and inadequate opportunities for subsequent homogenisation. Lack of equilibrium and its attainment during annealing also appeared to influence the phenomenon of critical strain and the coarse grain recrystallisation resulting therefrom, thus showing that the process of recrystallisation is related to the attainment of structural equilibrium in the alloy.

Comprehensive research on strain ageing, hardening and softening of metals by fatigue has been undertaken under the auspices of the United States Atomic Energy Commission[44]. Experiments were carried out at room temperature to ascertain the conditions under which true fatigue limits occur in aluminium-magnesium alloys. It was found that fatigue limits occurred in the solution heat treated specimens, but not in the extruded specimens. Metallographic examination showed that increase in the magnesium content reduced the width of slip marks (striations), which occur during fatigue. The amount of surface cracking was also reduced with increase in magnesium content. Tensile tests at $-196°C$ subsequent to fatiguing at $-196°C$ with intermediate resting at -80 to $+20°C$ showed hardening and softening effects due to interaction of vacancies and solute atoms with dislocations. A study of fatigue deformation in the interior of aged aluminium-magnesium alloys containing zinc added in various proportions to form ternary Al-Mg-Zn alloys, has been reported by Polmear and Bainbridge[45]. They found that in alloys which had a high zinc content, the fatigue property was essentially a grain boundary phenomenon, and cracking was intercrystalline. As the Mg : Zn ratio was increased, deformation occurred within the grain but was concentrated in certain slip bands along which cracking could occur. Cavities were observed in these slip bands and appeared to precede the formation of an actual crack. Zones, which were depleted of precipitate formed on ageing, were observed adjacent to slip bands in heavily deformed regions. Wilson[46] has postulated that these zones are formed by a process of resolution of the precipitate. As the Mg : Zn ratio was increased still further, the fatigue process was accompanied by little visible evidence of deformation. This structural stability has been attributed to the relatively high magnesium content, so that such alloys have the best fatigue properties.

Asnis and Coworkers[47] studied the impact strength of argon arc welded joints in Al-6% Mg alloys and observed that there was no notable difference between the impact strengths of metal at the fusion boundary, in the heat affected zone or in the parent metal. The single shock resistance strengths at $+10°$, $-20°$ and $-60°C$ were almost identical. At $-20°$ and $-60°C$ the welded test pieces sustained more impacts than automatic submerged arc welded mild M-St rimming steel or low alloy test pieces. Under repeated loading also welded Al-6% Mg alloy test pieces were found to be stronger than the mild or low alloy steel test pieces.

Conclusions

The work reviewed above leads us to the conclusion that, even though commercial aluminium-magnesium alloys having high magnesium contents are very susceptible to fracture when hot-worked, their properties can be modified by addition of small quantities of other alloying elements such as chromium, manganese, zinc, etc. Addition of rare earth group of metals, of which we have rich resources in India, has been observed to similarly modify the properties of aluminium and magnesium. It would be of interest to study the effect of such additions on the properties of high magnesium content aluminium-magnesium alloys, with particular reference to their hot workability, tensile strength and other high temperature properties. Work on these lines has already been initiated at the National Metallurgical Laboratory and interesting results have been obtained[48] which indicate that misch metal treated aluminium-magnesium alloys can be hot worked to sheet form. In the wrought condition, these alloys have mechanical properties comparable with those of "duralumin" type alloys and/or of steel.

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References

1 C. F. Light Metals Bulletin, *22*, 862 (1960).

2 Doyle, M. M., J. R. Aero. Soc. *64*, 535 (1960).

3 Shiletyaev, B. F. and Aleramora, Z. A., Khim, Mashinostroenie (2), 34, 1959.

4 Kempf, L. W. "Age Hardening", Amer. Soc. Metals (1940).

5 Kato, M. and Nakamura, Y., Keikinzoku (Japanese), No. 11, 58 (1954).

6 Whitaker, M. E., Proc. Inst. Brit. Found. *46*, A236 (1953).

7 Cibula, A. and Ruddle, R. W. J. Inst. Metals, *76*, 361 (1949).

8 Jay, R. and Cibula, A., Proc. Inst. Brit. Found. *49*, A125 (1956).

9 Metals Hand Book—A.S.T.M., Pitsburg 1948.

10 French Patent No. 988, 625—August 31, 1951.

11 Beck, A., Siebel, G. and Vosskuhler, G., German Patent No. 968, 234 (1958).

12 Rutemiller, H. C., U.S. Pat. No. 2,922. 731 (1960).

13 Modern Transport, *83*, 13 (May 1, 1960).

14 Guilhaudis, A. and Daveley, R., Revue Met., *54*, 281 (Apr. 1954).

15 Light Metals Age, *18*, 31 (August 1960).

16 Willmore, C. B., U.S. Patent 2,733,991 (Feb. 7, 1956).

17 Nachtigal, E. and Landerl, H., Aluminium Ranschfen, *4*, 15 (April 1956).

18 Ushioda, T., Yoshimura, O. and Mashiyama, S., Light Metals (Japan), No. 27, 29 (Nov. 1957); LMB *20*, 423 (1958).

19 Boswinkel, H., Metallen *10*, 237 (1955).

20 Ransley, C. E. and Talbot, D. E. J., J. Inst.Metals, *88*, 150 (1959–60).

21 Junghans, S. Brit. Patent No. 742, 641 (25 Sept. 1950).

22 Westinghouse Co. Ltd., Patent.

23 Buinov N. N., and Lerinman, R.M., Tridy Inst. Fiz. Metal, Akad. Nauk. SSSR, Ural, Fllial, *14*, 3 (1954).

24 Buinov, N. N., Leriman, R· M., Tridy Inst. Fiz., Metal, Akad. Nauk, SSSR, Ural Filial, *14*, 10 (1954).

25 Buinov, N. N., Leriman, R. M. and Gusimov, A. F., Tridy Inst. Fiz. Metal, Akad, Nauk SSSR, Ural Filial, *14*, 13 (1954).

26 Peganelli, M., Aluminio, 26, 353, (1957).

27 Pollard, W. A., Canada Dept. of Mines and Tech. Surveys, Mines Branch, Report No. RM221, Physical Metallurgy Divn., 30 pp., Nov. 6, 1957: Abstr. in Light Metals Bull, 20, 477, (1958).

28 Stubhington, C. A., Metallurgia, *57*, 165 (1958).

29 Saulnier. A., Rev. Aluminium, *32*, 1011, (1956).

30 Guilhaudis, A., Rev. Aluminium, *32*, 717 (1955).

31 Production Engineering, *31*, 17, 20, (March 7, 1960).

32 Mori, L. Allumino, *29*, 351 (July-Aug. 1960).

33 Johnson, E. W., Chem. Engg., *67*, 133 (1960).

34 Maltsev, M. W., Chistiyakov yu.D., Isypin, M. I., Doklady, Akad. Nauk SSSR, *99*, 813 (1954).

35 Smeltzer, W. W., J. Electrochem. Soc. *105*, 67 (1958).

36 Polmear, I. J., J. Aust. Inst. Metals, *1*, 169 (1956).

37 Hugony, E. and Monticelli-papania, M., Aluminio, *25*, 373 (1956).

38 Hugony, E., Metals Rev. *30*, 39 (Nov. 1957).

39 Erdmann-Jesnitzer, F. Herkst. u. Korrosion 9, 8 (1958).

40 Vance, W. J., A. Appl. Chem. *8*, 18 (1958).

41 March, L. L., Manniger, R. E. and Manning, G. K., U.S. National Advisory Committee on Aeronautics (NACA) Tech. Note 3681, 44 pp, (1956).

42 Grin, A. G., Fiz. Metal 2, Metalloved, Akad. Nauk. SSSR., *4*, 383 (1957).

43 Rosenkrauz, W., Aluminium, *38*, 390 (July 1956).

44 United States Atomic Energy Commission, Report No. AFOSR–TN–59–774 for 1957 (Feb. 1959).

45 Polmear, I. J. and Bainbridge, I. F., Phil. Mag. *4*, 1293, (1959).

46 Wilson, D. V. Acta Met. *5*, 293 (1957).

47 Asnis, A. E., Rabkin, D. M. and Savich, I. M., Automatic Welding, 22–29 (Nov. 1959).

48 Trehan, Y. N., Gupte, P. K. and Nijhawan, B. R., "The effect of misch metal addition on the structure and workability of Al–Mg (7–10%) alloys. Paper presented at the Symposium on "Light Metals Industry in India" held at NML, Jamshedpur in February 1961.

DISCUSSIONS

Mr. H. P. S. Murthy, NML: Dr. Trehan in the course of his address stated that when the sodium bearing Al-Mg alloys are heated to a particular temperature and worked, the sodium migrates to grain boundaries and causes large pores which later on result in alligator cracks. As this is rather intriguing, could Dr. Trehan elaborate on this subject ?

Dr. Y. N. Trehan, NML: Ransley and Talbot have said that during working, slip bands are formed and elemental sodium (when present) deposits on these slip bands creating pores, as has been shown in the last slide. I think it is quite a plausible explanation. However, the phenomenon is dependent upon the amount of sodium present. No crocodile cracks are formed when the amount of sodium is small (i.e. below 0·001%).

Dr. Ing. S. S. Khanna, Banaras Hindu University, Varanasi: The investigations carried out by W. Schumacher in Wengern (Ruhr), W. Germany, showed that the strength value of the CO_2 hardened sand in the temperature range 400-800°C are very low. The application of this process in the casting of light metals and alloys offers special advantages in that the time of removing the cores from the castings is considerably less and a fine surface finish is obtained.

Dr. Trehan (Author): I would thank Dr. Khanna for his information. We hope we will be able to make use of it.

Mr. R. Choubey, NML: Regarding the mechanical properties—the tensile strength, hardness, etc. in the as-cast as well as in the heat-treated conditions, one particular point occurred to me. While the tensile strength curves in the heat-treated condition have shown the normally high values compared to the as-cast specimen the hardness values have not shown similar nature. Although there is no exact correlation between tensile strength and hardness properties in general, they should give a rising tendency in either case. My point is why in the heat-treated condition and in the as-cast condition should they give similar figures ?

About the crocodile jaw cracking referred to by Mr. Murthy, I may mention by the way that this type of defect occurs during the rolling of coarse grained brittle materials. What happens is that during rolling, if the ingot centre is weak either due to very coarse grain size or some other defects such as segregation, etc. and if the mechanical working is done in stages so that the surface gets refined in structure and the centre remains weak due to coarse grain size, then in subsequent rolling the surfaces follow the rolls in two directions, up and down. This leads to such type of cracking ; so the addition of sodium might be influencing the brittleness of the material or leading to coarse grain size and during working the surface gets refined and the centre is weak leading to such type of cracking.

Dr. Trehan (Author): There is practically no difference in the hardness of these alloys in the solution heat-treated condition over the as-cast condition probably because the harder constituents are easily assimilated throughout the structure. However, there appears to be no such correlation in the tensile strength. It will be seen that in the as-cast specimens the tensile strength gets lowered beyond a magnesium content of 6% whereas in solution heat-treated condition, it shows a sharp rise and goes to a maximum at about 11% Mg. Why is it so? Probably because during heat-treatment, more of the magnesium goes into solid solution and this super-saturated Al-Mg solid solution, being in a state of strain, may have a higher tensile strength. This strain, however, does not seem to affect the hardness, which remains practically the same in both as-cast and solution heat-treated specimens. I hope this answers Mr. Choubey.

Mr. M. B. Shankar, Hindustan Aircraft Limited, Bangalore: One of the earlier speakers wanted to know from me the progress made on the supersonic aircraft being developed in HAL. I may state that the prototype, involving considerable problems of development, has nearly reached its final stage. I am sure, it will be successful in its test flights. All of you will, no doubt, read about it in the papers soon.

Now reverting to the discussions of the paper—regarding Mr. Murthy's question, I may explain that Na is immiscible in aluminium in the solid state. Some elements present in Al alloys may only affect liquid miscibility. As far as I am aware, Na is used as a deoxidiser in the light alloy foundry with its effectiveness still questionable. The other of its uses is as a modifying agent for Al-Si alloys. In the presence of Mg, I am afraid, Na forms Mg-Na which is decidedly detrimental and seriously affects working properties of the alloy. The alligator cracks reported in the forging of the Al-Mg treated with Na may, therefore, not be unexpected.

As regards Mr. Murthy's comment that sodium in such trifling quantity as 0·0018% cannot have any influence on crocodile-jaw tearing, may I emphasise that impurities in very minute or microscopic quantities have pronounced influence on the behaviour of metals and alloys. The microscopic impurities are entrapped at the grain boundaries, leading to intercrystalline embrittlement.

Alligator tears in forging operations are met with also in coarse grained structures. Apart from compositional controls, successful hot working depends upon careful control of working conditions. Defects also are, so to say, introduced by working conditions.

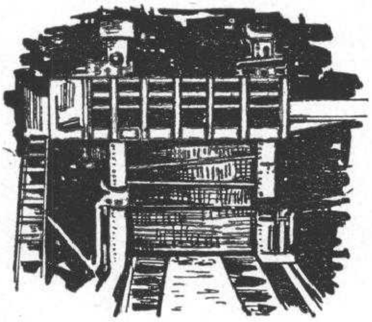
Dr. B. R. Nijhawan, NML: Mr. Shankar has said that the previous two speakers were perhaps right. To this I might add that Mr. Shankar is also equally right. In this connection, explanations offered to explain certain observed metallurgical phenomena very often attempt to explain away the latter instead of measuring up to the requisite expectations. With the onset of some excellent hypotheses based on studies of dislocations, vacant lattice sites, atomic clusters and impurity atom concentrations at mosaic disjunctions, many explanations based on the interpretations of these hypotheses have at times attempted to explain observed metallurgical phenomena. Some may tend to call them mere conjectures whilst others may justifiably regard them as scientific explanations to explain away complex metallurgical observations on the basis of almost unlimited flexibility of the explanations offered to suit, not unoften, fundamentally opposed metallurgical phenomena.

The light alloys, it was stated, were difficult to handle, but steel was relatively still more difficult to handle. Minute additions of boron to the extent of 0·002% can considerably alter and improve the hardenability of steel and used in conjunction with molybdenum can confer very high tensile and good weldability characteristics. It is not known exactly how boron does it, but there is a fair amount of surmises about it. It is a virgin and fertile field for metallurgists and physicists to let their imagination and therefore explanations run riot. But one has to basically accept the observed phenomena rather than explanations relating to observed physical properties and metallurgical characteristics. Similarly, take the case of Al in steel added to the extent of 0·02 to 0·03%, which can amazingly increase their Impact Test performance by about 7 times. Aluminium-treated mild steel containing 0·02–0·03% Al, might give an impact of 80–90 ft lb whereas a non-treated steel may give an impact test values of 10–25 ft lb. For this there had been offered several explanations. Thus sodium or inter-crystalline brittleness could also possibly be explained in this manner. While I do agree that physical concepts are most valuable and one can't do without them, one tends to acquire the habit of conjuring up some concepts to explain away the observations. As I said before, 0·02% of Al does not materially change the hardness of the steel at all but improves its impact test values about 7–8 times and this correlation of hardness vis-a-vis other physical properties is in my opinion rather erroneous. These did not always follow the straight curve and we cannot attach too much importance to them. If I may put it rather plainly, even if the hardness might increase or decrease, one cannot expect the tensile or even the impact test properties to follow the same order. It can be quite the other way about. This subject is now coming into the forefront on the basis of micro-metallurgy. Just as additions of rare earth group of metals can improve the life of nichrome heating elements very significantly in some unexplained way, this subject will be left to one's imagination, of course supported by mathematical and practical data, wherever possible. Mr. Murthy doesn't like sodium obviously, but there is nothing to worry about it; maybe sodium functioned that way. What is exactly happening at the intercrystalline boundaries is very difficult to precisely explain. The failure of the welded Liberty Ship during the last War, when the ship broke up into two, also gave rise to considerable research and development work; this failure took place through brittle failure—these are potential fields for active research scrutiny. Now coming to Dr. Trehan's predicament, I would say he could explain it by falling back on dislocations or vacant lattice sites or intercrystalline precipitation of something you may never really observe. The effects of micro-additions of several elements are very unpredictable. Supposing the addition of 0·02% of Al in the case of steel gave a considerable improvement in impact toughness both at room and elevated temperature, and appreciably lowered transition temperature range, that was a very desired property indeed.

Following the same analogy, if we add additionally 0·02% aluminium, the whole process reverses and coarsening of the austenitic grains starts. In what ways these elements like Al, N_2, C—whether by forming aluminium nitride or through some other mechanisms—that were still to be fully explored. I am sure, Prof. Bashforth will agree with me in accounting for several of these unexplained phenomena encountered in the steel-making processes. It is not a matter of despair that these cannot be adequately explained.

Dr. Trehan (*Author*) *:* Reverting to Mr. Shankar's remarks that anything can happen with micro-addition of Na, particularly when the conditions are dissimilar, I would say that the report from Ransley and Talbot shows that they used the material from the same heat, casting a small portion and then adding Na and so on. All the 4 specimens were prepared from the same heat but contained different amounts of Na, so that the only variable was Na. There is nothing else to expect than to say that the only condition which is causing the crocodile failure is the additional quantity of Na in these alloys.

We have also encountered crocodile tears in our work. This is dealt with in our second paper*. But our analyses did not show the presence of sodium in our alloys. The failures in these cases may have been due to coarseness of the grain.



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* Trehan Y. N., Gupte, P. K. and Nijhawan, B. R.: "The Effect of Misch Metal Additions on the Structure and Workability of Al-Mg (7–10%) Alloys" (page No. 90).