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Microalloying Effects of various Metals on 2xxx series aluminium Alloys - A Review Paper

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Abstract
The search for new materials with enhanced properties for industrial and structural applications has led to the development of many metallic alloys. A metallic alloy is a solid solution made of two or metal elements or metal and non-metal elements in a metallic matrix. Alloys can be a homogenous solid solution, a heterogeneous mixture of tiny crystals, a true chemical compound or a mixture of these. Alloys tend to have properties which are often superior to that of their constituent elements. The alloys of aluminium are basically of two types: Heat Treatable and Non Heat Treatable. The heat treatable aluminium alloys are broadly grouped under three series namely 2xxx series (with Cu as principal alloying element and Mg as secondary addition), 6xxx series (with Mg and Si as principal alloying elements) and 7xxx series (with Zn, Cu, and Mg as principal alloying elements). It is observed that in different countries there are various investigations are carried out on 2xxx (Al-Cu-Mg) Al-alloys with different alloying elements. The phenomenon of strengthening in commercial Al-alloys is well established and the developments has almost saturated. The present trend in improving the Mechanical properties of these light weight alloys are by micro-alloying. In this review paper the effect of microalloying on 2xxx series Al-alloys by using various metals are discussed elaborately.

Keywords: Heat treatable aluminium alloys, 2xxx Series Al-alloys, Microalloying.

Introduction
The metallic alloys are developed to achieve improved properties which can be used in various industries. An alloy can be defined as a solid solution which has more than one metal or nonmetal element in it. Alloys may be a heterogeneous mixture of small crystals, homogeneous mixture of elements, a pure chemical mixture or combination of all these. It is confirmed that alloy possesses improved properties which are not present in the individual elements. Their so many examples present in day to day life e.g., Steel is an alloy of iron and carbon. Steel has improved properties than iron and it is used broadly in various industries. In comparison with ferrous alloys, nonferrous alloys are widely used in aerospace industries. This is due to ferrous alloys shows higher density and insufficient electrical and thermal conductivity as compared to nonferrous alloys. Due to the increasing interest in aerospace industries, researchers developed several light weight alloys with improved mechanical properties.
Researcher’s main center of interest is in developing aluminium, titanium, etc. alloys. Besides all other alloys, aluminum alloys have good strength to weight ratio and due to these aluminium alloys get more interest from researchers. The 2xxx, 6xxx and 7xxx series alloy were extensively explored and developed. The mechanical properties of these alloys are influenced by variation in composition, applying various heat treatment conditions, thermo-mechanical treatments, etc. The present trend in achieving materials exhibiting high strength to weight ratio is by micro-alloying *i.e.*, by the addition of trace amounts (<0.1 wt%) of elements like Sn, Zr, In, Cd, Ag, Ti etc.

Aluminium Alloys
Cast and wrought are the main classes of aluminium alloys. In automobile industries, Al-Mn, Al-Mg, Al-Si alloys are widely used. Al-Mn, Al-Mg, Al-Si alloys have good fluidity and hence they produce good castings. Al-alloys are widely used in wrought form because of their high strength and high strength to weight ratio. By applying precipitation hardening process these strength is achieved. Alfered Wilm in 1906 first investigated to develop the strength of Al-alloys by age hardening [1]. The alloy was known as Duralumin and the process of strengthening was not understandable for long time. After 16 years the strengthening mechanism was known and due to lack of technology the precipitation phases were not seen.

In the year 1935, with the help of X-ray diffraction the phenomenon was observed and the precipitation of phases was seen. The theoretical analysis of the effect of hardening during age hardening treatment of Al-Cu alloys was done IN 1948 [2]. In the year 1959, after invention of Transmission Electron Microscope (TEM) the nano sized Guiner-Priston zones (GP zones) were observed. In Al matrix, due to the clustering of Cu atoms on the {100} planes GP zones were generated. Researchers developed 2xxx, 6xxx and 7xxx alloys gradually which have their own application and disadvantages [3].

In case of 6xxx series Al-alloys, Mg and Si are the main alloying elements. However, in 7xxx series Al-alloy, Zn is the main alloying element. These are heat treatable Al-alloys with high strength. These are widely used in aerospace industries [3].

Copper (Cu) is the main alloying elements in the 2xxx series Al-alloy but in some cases, along with Cu, Magnesium (Mg) is also used as a main alloying element. Cu gives strength to the alloy by precipitation hardening with or without Mg. Alloy with low Cu content such as 2024 and 2014 shows good corrosion resistance, formability and spot weldability and these are widely used in automotive industries [3, 4]. In 2xxx series Al-alloys, Al-Cu-Mg containing alloy like 2218, 2219 and 2618 are used in aerospace industries [5, 6, 7, 8]. In fig.1 various types of Aluminium alloys with their applications are shown.

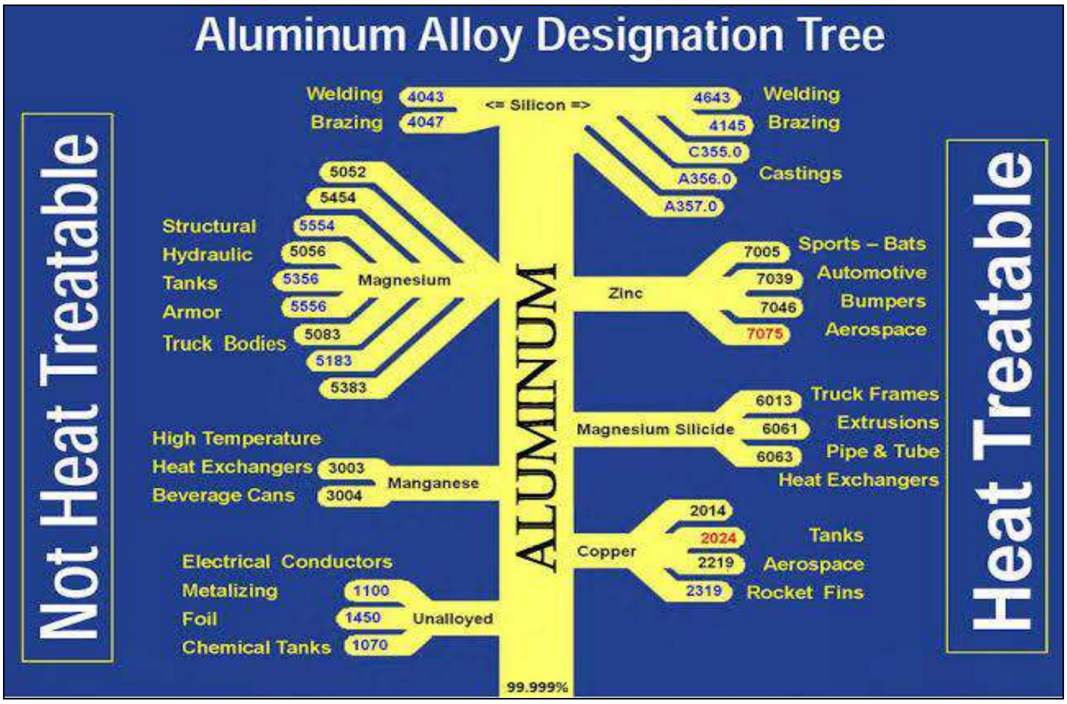

Fig.1. Types of Aluminium alloys [source: https://www.google.com/search?q=Heat-Treatable+and+Non-Heat]

Effect of alloying elements in Aluminium alloys

Researchers studied the effect of alloying elements like Cu, Mg, Fe, Si, etc. on mechanical properties of commercial aluminum alloys. The process involved in the strengthening of non-precipitation hardening wrought aluminum alloys is governed by either grain refinement or solid solution strengthening or both. To find the yield strength and other mechanical properties w.r.t grain size Hall-Patch equation is used.

In case of strengthening based on solid solution, Hume-Rothery rule have to be fulfill. According to Hume-Ruthery rule, the criteria that come under consideration are as follows:

a) The atomic radius of the solute and solvent atoms must differ by no more than 15%,
b) The crystal structure of the solute and solvent must be similar,
c) Complete solubility occurs when the solvent and solute have the same valence furthermore, lower valence metal likely to be dissolve in a metal of higher valence and
d) The solute and solvent should have similar electronegativity. After fulfillment of Hume-Ruthery rule, the strengthening of the solid solution is reached by electron-atom ration of the alloy.

From literature it is observed that most of the researchers studied the effect of common alloying elements on structure and properties of 2xxx series Al alloys. Some of them are mentioned below:

Copper (Cu): Strengthening and precipitation hardening mechanisms are increased by copper (Cu) addition in Al alloys. In ageing process the precipitation of $CuAl_2$ or $CuAl_2Mg$ phases occurs and thus the hardening of the alloy is derived. By the addition of Cu, machinability, properties at high temperature, etc. are improved but excess Cu (> 6%) is not wanted in case of corrosion resistance applications. If the amount of Cu is high then the alloy is prone to several defects such as pitting, stress corrosion, etc.

Magnesium (Mg): Strain hardening and strength of the alloy are increases by Mg addition in Al alloys. At room temperature ageing, Mg increases the strength and ductility of some wrought alloys. In case of ageing artificially, Mg increases the yield strength but decreases the elongation.

Silicon (Si): Adding high amount of Si in Al alloys increases the fluidity of the alloy which helps in casting of alloy in different forms. In case of 6xxx series Al alloy Si combine with Mg and form Mg_2Si which increases the strength of the alloy after heat treatment.

Manganese (Mn): Adding Mn in Al alloy increases the strength and strain hardening of the alloy by developing fine precipitate phase. During the process hardening is achieved without hampering ductility and corrosion resistance. Adding Mn and Mg, increases the tensile and yield strength but Mn reduces the ductility of the alloy. Hence, it is suggested that Mn should be added ≤ 1%.

Iron (Fe): It is observed that during heat treatment Fe decreases the tensile properties of Al-4%Cu-0.5%Mg alloy. Fe increases the strength of the alloy Al-Cu-Ni at high temperature [9].

Zinc (Zn): Zn combine with Cu and Mg increases the strength of the Al alloys [9].

Silver (Ag): Adding ≤ 0.1% Ag in Al alloy increases the strength of the aged Al alloys [9].

Cadmium (Cd): Adding Cd ≤ 0.3% in Al-Cu alloys improves the rate of age hardening [9].

Indium (In): Adding In ≤ 0.2% in Al-Cu alloys decreases the aging time at room temperature [9].

Vanadium (V), Zirconium (Zr) and Titanium (Ti): Adding V, Zr and Ti in Al-Cu alloys make the alloys capable of hold the properties at high temperature. Ti acts as a grain refiner in most of the Al-Cu alloys [9].

Nickel (Ni): Adding Ni ≤ 2% improves the strength of the alloys but decreases the ductility [9].

Lead (Pb): Adding Pb improves the machinability of the alloys [9].
Hence it is seen from the above discussion that the field of general alloying is now saturated and researchers are trying to invent some modern advanced method of alloying by which they can developed alloys having high strength, corrosion resistance, favourable toughness and low density. One technique by which above properties can be achieved for an alloy is microalloying.

2. Series Al-alloy

Processing of 2xxx series aluminium alloys plays an important role in determining its mechanical properties. Properties of aluminium alloys also depend on its microstructure, average grain size and its distribution, volume fraction of precipitate and the crystallographic orientation. Hence, processing and compositions are two important tools in determining the mechanical properties of this alloy. The heat treatable 2xxx series aluminium alloys are processes in the following steps: Casting and homogenization, hot working, cold working, annealing and ageing treatment. Presence of metastable phases as well as coring and segregation is expected in the as-cast microstructures of the alloys. These result in non-homogenous distribution of the elements thereby resulting in variation of the mechanical properties across the casting section. To ensure a homogenous composition, removal of any metastable phases, coring and segregation formed in the as-cast alloys, they were subjected to homogenizing heat treatment followed by solution heat treatment in a furnace. The temperature and time of homogenizing heat treatment and solution heat treatment are varied alloy to alloy which are available in ASM hand book vol.4.

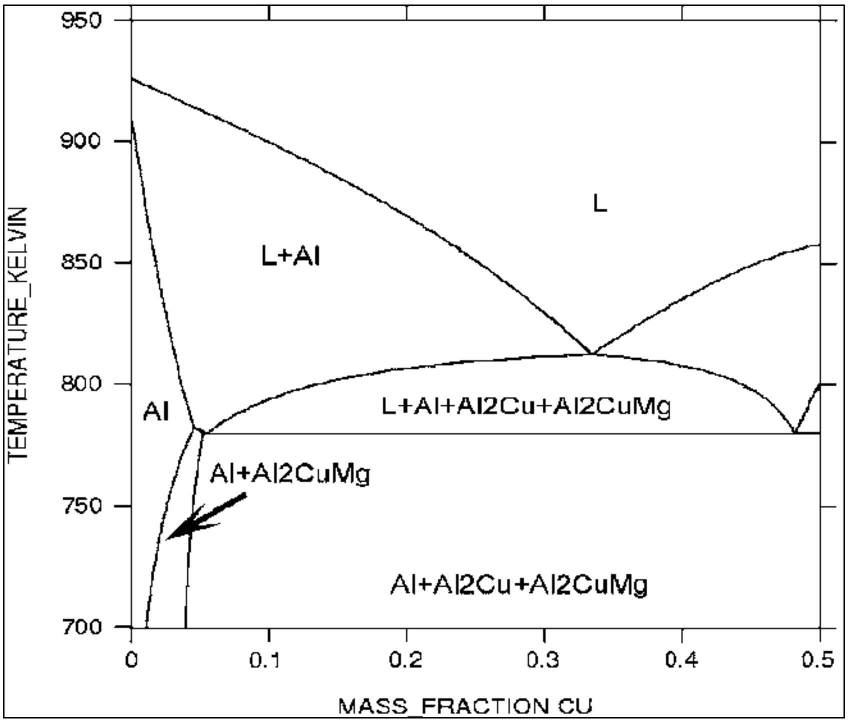

Fig.2. A part of the Al-Cu-Mg phase diagram [Source: https://www.researchgate.net/figure/Vertical-section-of-the-ternary-Al-Cu-Mg-phase-diagram-with-the-weight-fraction-of-Mg_fig3_227096224]

The major 2xxx aluminum alloy systems with precipitation hardening include:

- Aluminum-copper systems with strengthening from $CuAl_2$
- ·Aluminum-copper-magnesium systems (magnesium intensifies precipitation) [3].

From fig.2. it is observed that in Al-Cu-Mg alloy system the basic element is Cu amd Mg. Thus it is called heat treatable alloy. This heat-treatable alloy may in the T4 temper condition (solution heat treated condition) and T6 temper condition (precipitation heat treatment).

Table. 1: Compositions of some 2xxx series Al alloys in wt %
[Source:https://www.substech.com/dokuwiki/doku.php?id=wrought_aluminum copper_alloys_2xxx]

Designation	Si,%	Cu,%	Mn,%	Mg,%	Ni,%	Ti,%	Others,%
2011	0.4 max	5.0-6.0	-	-	-	-	Pb=0.4, Bi=0.4
2014	0.5-1.2	3.9-5.0	0.4-1.2	0.2-0.8	-	0.15 max	-
2017	0.2-0.8	3.5-4.5	0.4-1.0	0.4-0.8	-	0.15 max	-
2018	0.9 max	3.5-4.5	-	0.4-0.9	1.7-2.3	-	-
2024	0. 5 max	3.8-4.9	0.3-0.9	1.2-1.8	-	0.15 max	-
2025	0.5-1.2	3.9-5.0	0.4-1.2	-	-	0.15 max	-
2036	0. 5 max	2.2-3.0	0.1-0.4	0.3-0.6	-	0.15 max	-
2117	0. 8 max	2.2-3.0	0.2-0.5	-	-	-	-
2124	0. 2 max	3.8-4.9	0.3-0.9	1.2-1.8	-	0.15 max	-
2218	0. 9 max	3.5-4.5	-	1.2-1.8	1.7-2.3	-	-
2219	0. 2 max	5.6-6.8	0.2-0.4	0.02	-	0.02-0.1	V=0.1, Zr=0.18
2319	0. 2 max	5.6-6.8	0.2-0.4	-	-	0.1-0.2	V=0.1, Zr=0.18

In the table 1 the compositions of various 2xxx series Al-alloys are shown and from that it is observed that in Al-Cu-Mg alloy system the Cu amount (in wt.%) is varied from 2.2 – 6.8 wt.% and Mg amount (in wt.%) is varied from 0.02-1.8 wt.%.

Effects of micro alloying on Al-alloys

The addition of a small amount of rare earth elements has a large influence on the structure and properties of Al alloys. Scandium (Sc), having both properties of transition metals and rare earth elements, has received high attention. In most cases, Sc addition in the 1xxx (pure Al) [10], 5xxx (Al–Mg) [11], 7xxx (Al–Zn–Mg) [12] series alloys showed remarkable positive effects on the properties, such as modification of the as-cast structure [13, 14], improvement in the ambient and high-temperature mechanical properties [15, 16]. From fig.3 improvement of hardness is observed with aging temperature.

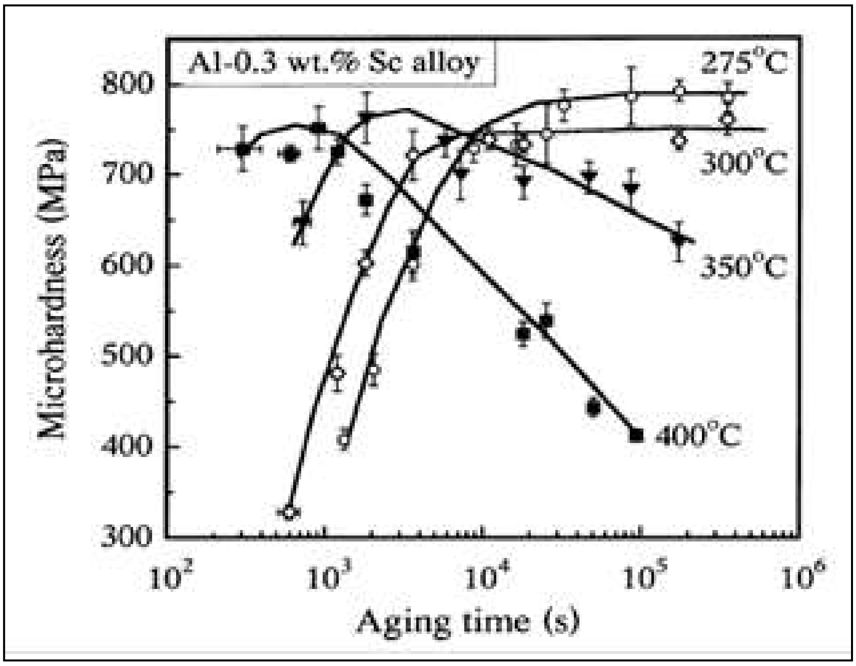

Fig 3: Vickers micro-hardness versus aging time for an Al- 0.3 wt. % Sc alloy as a function of aging temperatures (275, 300, 350 and 400 °C)[16].

Recently researches have reported the effect of micro-alloying in 2xxx series Al-alloys with Sn, Zr, In, Cd, Ag, etc. The focus of these studies was on the effect of trace (<0.1 wt %) additions of these elements on the microstructure, mechanical properties and corrosion resistance, precipitation kinetics and hot deformation behaviour of commercial alloys. Micro-alloying with different elements *viz*., Sn, Cd, In, Ag, Si etc. have been attempted to develop materials with improved properties. Addition of more than 0.06 wt% Sn caused increase in the ductility and toughness but reduction in the strength and hardness of the cast alloys shown in fig.4 [17].

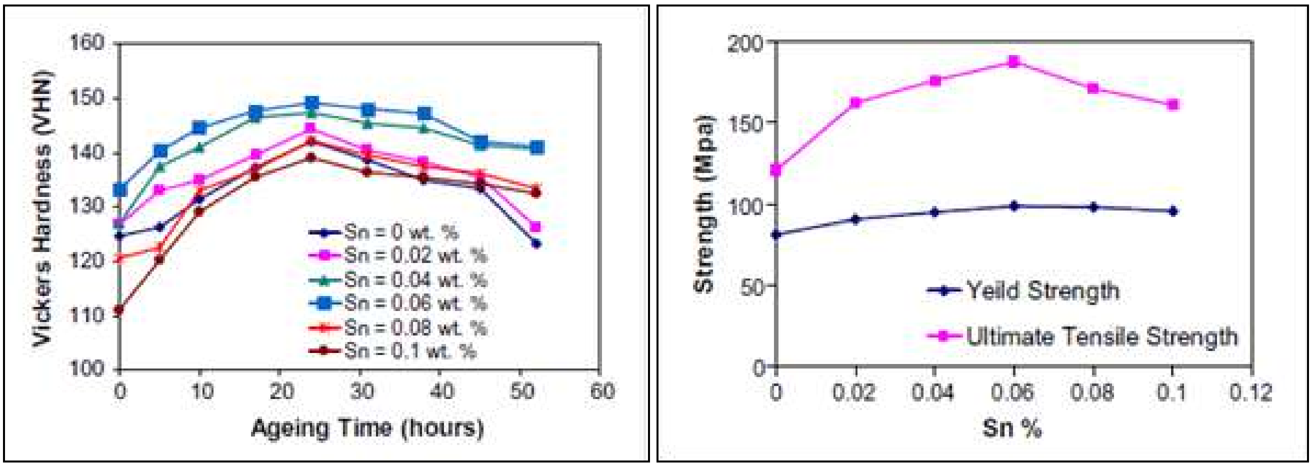

Fig 4: Variation of hardness, YS and UTS with Sn content [17].

Addition of 0.06 wt. % of Sn resulted in the improved mechanical properties for Al–7wt%Si–0.35wt% Mg alloy. The average grain diameter of the annealed alloy was found to increase with increase in Sn content up to 0.06 wt. %. Reduction in the grain size was observed with further increase in the trace additions of Sn.

Addition of Ag resulted in the improvement in the yield strength with the reduction in ductility. However, no effect on grain refinement or re-crystallisation was observed. Moreover, the strength observed by the addition of Ag was higher than that due to θ′ precipitation. From fig. 5 it is observed that addition of 0.3 %wt. Ag in 2519 Al alloy accelerated age hardening and increased peak hardness at a precipitation temperature of 180°C [18].

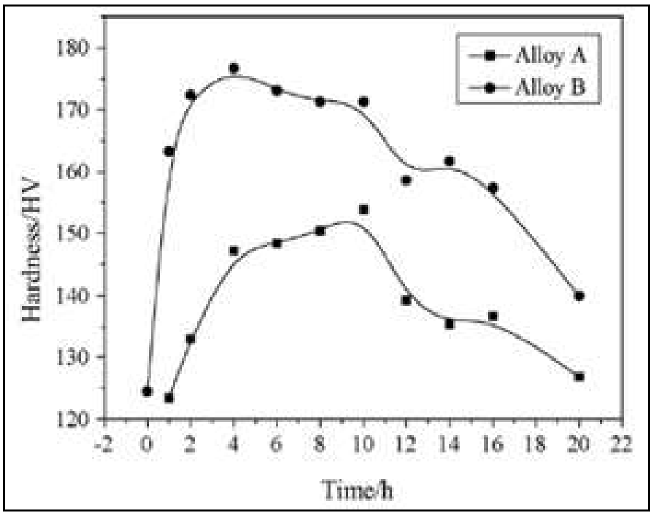

Fig 5: Age hardening behaviour of master alloy (Alloy A) and master alloy with Ag (Alloy B) [18].

Addition of Sc in Al–Mg alloys up to 0.4 wt. % resulted in the increase in strength. This was due to the formation of dispersed Al_3Sc particles in the matrix [19]. Addition of Zr intensified the effect of Sc addition and stabilized the structure of the alloys. Trace addition of Sc was found to improve the yield strength more than the tensile strength of Al-6 wt. % Mg alloys [20]. This is due to fine coherent Al_3Sc precipitates being more responsive to yield behaviour. The beneficial strengthening effect of these alloys was however found to be limited to 0.4 wt. % of Sc addition.

The literatures revealed that trace additions of Cd, In and Sn resulted in the accelerated ageing and higher peak hardness in Al–Cu alloys. This phenomenon was reported to be due to the formation of very small diameter platelets of θ′ in alloys containing Sn [21]. The effect of 0.2-0.51 wt. % Si and 0.69 wt. % Ge additions on the microstructure and hardness of 2219 Al-alloy during ageing was investigated by Maksimovic *et al.* [22]. It was found that for the same level of micro-alloying, the effect of small additions of Si and Ge in alloy 2219SG (containing Si and Ge) achieved a maximum hardness three times faster than in alloy 2219S (without Ge). The precipitation kinetics was accelerated due to the presence of fine Si-Ge particles which acted as heterogeneous precipitation sites for the metastable θ" phase. Addition of small amount of Ge also increased the hardness compared to alloy 2219S which is shown in fig.6.

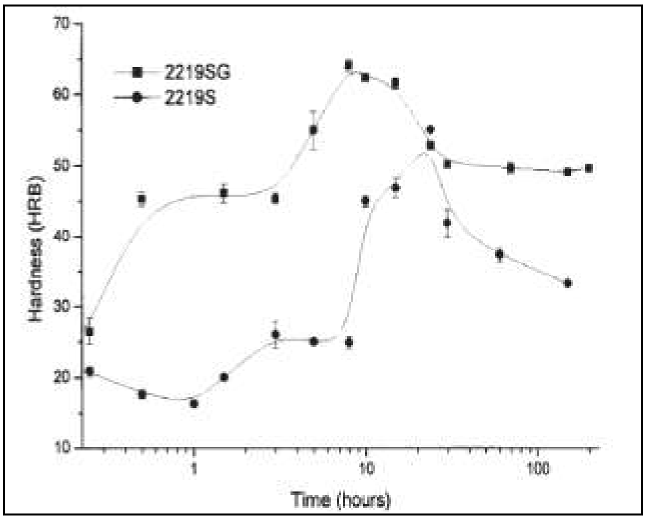

Fig 6: Change of hardness during aging at 190°C [22].

Investigation on the effect of trace addition of Sn and different heat treatments on the microstructure and mechanical properties of sintered 2xxx series Al-4.4Cu-0.8Si-0.5Mg alloys have been carried out [23]. Sn concentration was limited to 0.1wt% to avoid incipient melting during solution treatment. The study revealed a tensile strength of 375 MPa, which was almost 20 % higher than the alloy without Sn addition.

Röyset [24] provided an overview on Sc in Al-alloys in a review paper. Physical metallurgy, properties and applications of the alloys were also presented. Sc was observed to be a strong modifier for Al-alloys eliminating the dendritic microstructure. From fig.7 it is observed that, when 0.4 wt. % Sc and 0.2 wt. % Zr were combined and added in Al-4Cu-1.5Mg alloy, the as-cast micro structure of the alloy was effectively refined, and the crystalline grains of the alloy were refined to become fine and uniform equiaxed grains. Addition of 0.4 wt. % Sc and 0.2 wt. % Zr in 2xxx series Al-alloys resulted in the refine grain structure along with the improvement in the tensile strength, yield strength and elongation [25].

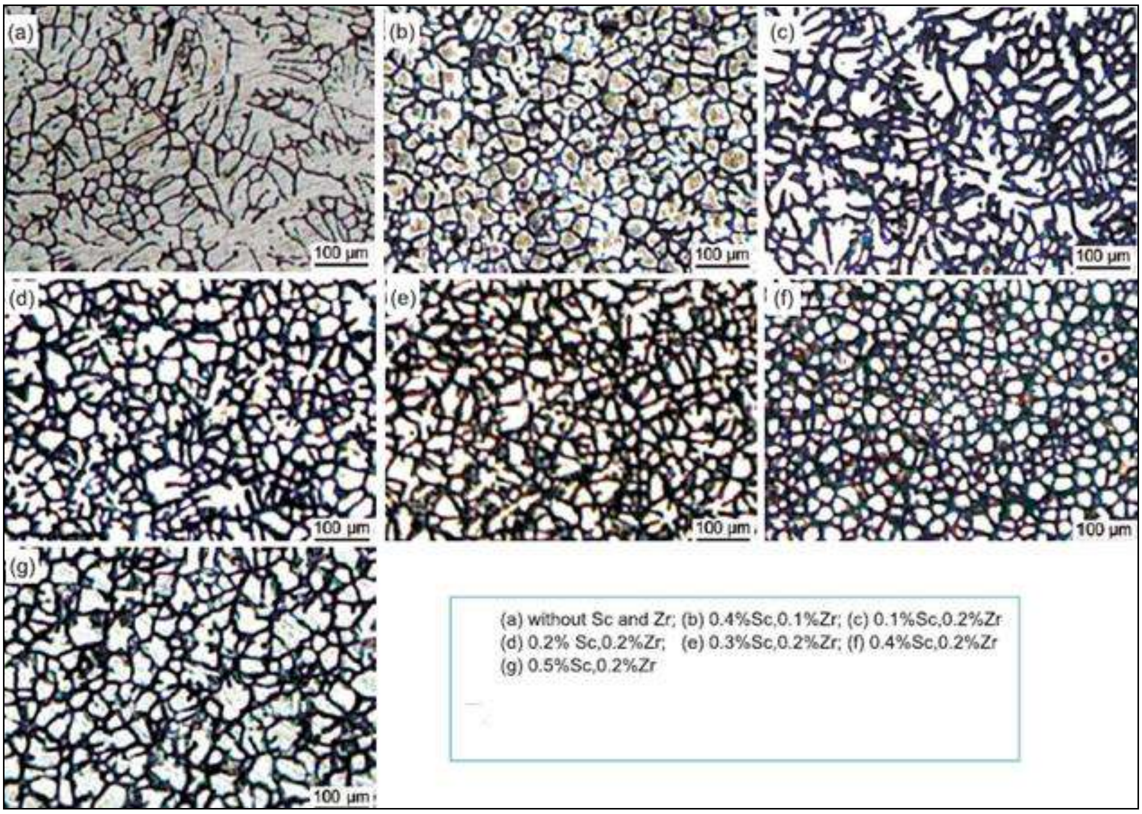

Fig 7: As cast microstructure of Al-4Cu-1.5Mg alloy with various addition of Sc and Zr [25].

Mukhopadhyay [26] contributed to a review work to highlight the influence of Ag on the properties of 2xxx series Al alloys. In the study on 2xxx series Al-alloy (Al-4Cu-0.5Mg-0.5Ag) by the author, two distinct second phase particles based on and in the as-cast alloy was observed. S (Al_2CuMg) phase was present as a minor phase and dissolves Ag, whilst the θ(Al_2Cu) phase represents the major phase and is based on Al-Cu-Mg. The latter is present as a minor phase and dissolves Ag, whilst the former represents the major phase and is based on Al-Cu-Mg. The Cu content of the major phase is similar to that of the θ phase, while the Mg content of this phase varies in the range of 0.7 to about 2wt%. Both Ag and Mg are located in excess amounts in the peripheral (implying particle/Al matrix boundary) regions of such phase. This phase is readily replaced by θ upon annealing at 450°C. It is pointed out that at the beginning, the Ag and the Mg atoms are integral parts of the solute atom clusters forming the Cu-rich θ and S phases. However, the insolubility of Ag and Mg in the θ phase requires that these two elements be rejected during the growth of the θ phase. This leads to the observation of an apparent segregation of Ag and Mg in the peripheral regions of such phase particles.

Zheng *et al.* [27] studied the microstructure evolution of the 1469 Al alloy (Al-Cu-Li-Sc alloy) during homogenization. The authors found no evidences of the Al3Sc phase and the W phase (Al-Cu-Sc) were found in the solidification structure. The arrays of the W phases were found to form after homogenization. The AlCu phases with traces of Sc that formed during solidification suppose to be the precursor of the W phases, and then transform into the W phases by consuming the Sc atoms that fixed in the supersaturate solid solution. The formation of the W phase inhibits the precipitation of the Al_3Sc phase.

K. Yu *et al.* [8] measured the tensile properties of a 2618 Al (Al–Cu–Mg–Fe–Ni) alloy containing scandium and zirconium were measured at 293, 473, 523 and 573K to study the temperature influences on the experimental alloys. The microstructure was observed by using optical microscopy, scanning electron microscopy (SEM) and transmission electron microscopy (TEM). It was found that the addition of scandium and zirconium to 2618 alloy resulted in a primary Al_3(Sc, Zr) phase. Such phase could refine the alloy grains because it acted as a core of heterogeneous crystallization during solidification. The strengths of the 2618 alloy with Al_3 (Sc, Zr) phases increased at both ambient and elevated temperatures, without a decrease of ductility.

Naga Raju *et al.* [28] studied the microstructure and high temperature stability of age hardenable 2219 Al-alloy (Al-6.3wt.%Cu alloy) modified by 0.2 to 0.8wt.% of Sc, Mg and Zr addition. He found that addition of Sc, Mg and Zr to the base metal resulted in improved high temperature stability due to formation of fine equiaxed grains, refined eutectics and large number of high temperature stable and finer precipitates. Out of the compositions, the alloy with additions of 0.8 % Sc + 0.45 %Mg + 0.2 % Zr was found to be the best in terms of high temperature stability.

Zlaticanin *et al.* [29] studied the early stages of transformation of a metastable AlCuMg alloy using DSC, X-ray powder diffraction method, quantitative microstructure analysis, hardness, compression strength and scanning electron microscope. Differential scanning calorimetry was done for the samples: AlCu15Mg1 (0%Ti), AlCu15Mg1 (0.25%Ti), AlCu15Mg2 (0.25%Ti), AlCu15Mg3 (0%Ti), AlCu15Mg3 (0.25%Ti), AlCu15Mg4 (0.25%Ti), AlCu15Mg5 (0%Ti), AlCu15Mg5 (0.25%Ti). This method produced DSC-curves, where endo thermal effects were present, on the basis of which the heat of transition was obtained. On increasing the magnesium and titanium content in the alloy, for the first and the second detectable endo-thermal effect, the value of heat of transition decreased. The formation of intermetallic compounds Al_2Cu and Al_2CuMg were monitored by X-ray powder diffraction. This method showed that a tetragonal intermetallic compound Al_2Cu and orthorhombic inter-metallic compound Al_2CuMg were formed for AlCuMg alloy.

Tensile test, micro-hardness measurements, transmission electron microscopy and scanning electron microscopy were studied in case of aged high purity Al−Cu−Mg alloy to know the pre-deformation effects on microstructure and mechanical properties. It was observed that in case of micro-hardness measurements, compared to un-deformed samples the peak hardness is increased and by increasing pre-strain the time of reaching the peak hardness is reduced. Aging at 453 K, double peak hardness is observed for cold rolled (CR) samples. TEM shows that with the increase of pre-strain the size is decreased in CR alloy and the number density of S'(Al_2CuMg) phase is increased. Due to quantity increasing and refinement of S' phase and high density dislocation peak hardness and peak strength of the CR alloy are increased [30].

Researchers studied the yield strength in dilute Al(Sc) alloys containing coherent Al_3Sc precipitates at ambient temperature and creep resistance between 225 and 300°C. The precipitates were formed because of heat treatment which had radii in the range 1.4–9.6 nm. At constant Sc amount, the time of peak hardness is decreasing with increasing aging temperature. After aging for about 50 h at 350°C or 0.5 h at 400°C, hardness decreases. This is observed due to coarsening of the Al_3Sc precipitates. Due to coherent Al_3Sc precipitates, the flow stress at room temperature increases from about 20 MPa for pure Al to 140–200 MPa for Al(Sc) alloys. Creep threshold stresses are indentified at 300°C and it is much lower than the yield stresses [31].

Researchers studied the precipitation behavior of Al–Cu–Mg–Ag single crystal under elevated compression stress while aging the crystal. For carry out the study researchers used high angle annular dark field scanning transmission electron microscopy (HAADF-STEM), Transmission electron microscopy (TEM) and hardness test. From the study it is observed that at 50 MPa compression stress the sample of the crystal shows uniform length distribution but it reduces the density of Ω-phase in the stress-aging samples with respect to stress free aging samples. On the other hand, at higher compressive stress of 200 MPa the samples shows that density of Ω-phase is rapidly reduces but along the dislocation line density of θ′-phase is precipitated in large number [32].

The alloy Al–2.5 wt.% Cu– 0.3 wt.% Sc was studied by using three-dimensional atom probe analysis to observed the Sc segregation at θ′/α-Al interfaces at aging temperature 473, 523 and 573 K, respectively. The results revealed that at 523 K-aged alloy the strongest interfacial Sc segregation is seen and greater interfacial Sc concentration is observed which was 10 times greater than that in the matrix where interfacial energy was reduced by 25%. The interfacial Sc segregation enhanced the θ′ precipitation and thus strength of the alloy also increase on the other hand, it decreases the ductility when precipitate radius is larger than 200 nm in the 523 K-aged alloy [33].

Studies were carried out in heat treatable alloy like Al–2.5 wt% Cu (Al–Cu) and Al–2.5 wt% Cu–0.3 wt% Sc (Al–Cu–Sc) which had varying grain length scales and were developed by by equal-channel angular pressing (ECAP). The varying grain length scales were considered as average grain size > 10 μm (defined coarse grained, CG), 1–2 μm (fine grained, FG), and < 1 μm (ultrafine grained, UFG). The effects of micro alloyed Sc, different length scales and their interaction between precipitation behavior and mechanical properties on Al–Cu alloys were examined elaborately. It was observed that in the Al–Cu alloys inter granular θ-Al_2Cu precipitation subjugated by the decreasing the length scale and sacrifice the intra granular θ′-Al_2Cu precipitation. In the study it was found that in UFG regime inter granular θ-Al_2Cu particles were precipitated and intra granular θ′-Al_2Cu precipitation were not seen. Thus it reduced the yield strength and ductility. The addition of Sc by micro alloying in the alloy showed favourable results. The micro alloying effect was more vigorous when size of the grains became smaller [34].

From the literature it is found that when Si is micro-alloyed with 2xxx series Al-Cu-Mg alloys, it accelerate the effect of age hardening and with this concept commercial alloys like 2618 are based on this philosophy. Researchers studied Al-2.5Cu-1.5Mg (wt pct) alloy micro-alloyed with Si to find the results of microstructural characterization. In the peak hardness microstructure fine and uniform dispersion of Si modified Guinier-Preston Bagaratsky (GPB) zones was observed. Another phase that was seen in the peak hardness microstructure was S phase but it does not take any part in enhancing hardness because of their coarse dispersion [35].

Due to trace addition of elements in aluminium alloys it is observed that it improves the mechanical properties of the micro-alloyed alloy by altering the precipitation process. Researchers studied Al-1.1Cu-1.7Mg (at.%) alloy by micro-alloying with Sn and (Sn+Ag). The effects of Sn and (Sn+Ag) addition in Al-1.1Cu-1.7Mg (at.%) alloy was investigated by combining series of hardness testing and transmission electron microscopy (TEM). Investigation revealed that harness of the alloy micro-alloyed with Sn increases all over the ageing process and if Sn was added with Ag to the alloy then hardness further increases and it reduces the peak hardness time [36].

From literature it is observed that studies were carried out for the alloy Al–Cu–Mg with and without Li additions. The study was to investigate the formation of precipitates and intermetallic phases in dilute precipitation hardening for the said alloy with and without Li. Literature revealed the best sequence of precipitation which was supersaturated solid solution → co-clusters → GPB2/S"→ S where GPB2/S" is said as orthorhombic phase and S phase is said as an equilibrium Al_2CuMg phase. The structure of S phase obtained from Perlitz and Westgren model is considered as the most accepted structure. From the literature it was observed that the shifting of GPI to GPII (or θ′′) was continuous and it was seen that the atoms of Cu not clustering together or they clustered with vacancies. Therefore the sequence of precipitation was like supersaturated solid solution → θ′′ (Al_3Cu) → θ′ (Al_2Cu) → θ′ (Al_2Cu) [37].

Researchers investigate the alloy Al–Cu–Mg with high Mg:Cu ratio micro-alloyed with Ag to know the effect of Ag on the precipitation process of the alloy. Investigation was carried out during artificial ageing of ternary and quaternary compositions Al–1.5 wt. %Cu–4 wt. %Mg(–0.5 wt.%Ag) at 175 °C where study of transmission electron microscopy and positron lifetime spectroscopy also included. The alloy without Ag shows that when quenching was done after solution heat treatment vacancy v-Cu–Mg clusters are formed in the supersaturated solid solution. The amount of Cu and Mg is more at the initial stages of ageing and nucleation shows on dislocation lines for laths of the S phase (Al_2CuMg). The alloy with Ag shows similar behavior of v-Cu–Mg–Ag aggregates and the same solute transport mechanisms. The S phase precipitation was concealed when ageing was carried out for alloy without Ag. On the other hand, the alloy containing Ag finer dispersion of smaller equi-axed Z phase precipitates were seen and the development was speed up due to Ag [38].

Researchers investigated the behaviour of artificial ageing settings for aluminum alloy 2024 by studying its precipitation kinetics, tensile and work hardening mechanical properties. The tensile samples are prepared for three artificial ageing settings like under-ageing (UA), peak-ageing (PA) and over-ageing (OA) after that the test is performed. At PA condition yield stress was increased and then it was decreased in elongation at fracture point. It was observed that within diffusivity rate of solute Cu and Mg atoms in the aluminum matrix the precipitation kinetics lie for the alloy. In case of work hardening analysis, it was seen that the stages of work hardening were sensitive to artificial ageing [39].

Due to the lack of literatures on the effect of overaging on microstructure and tensile properties of unconventional 2055 Al-Cu-Li-Ag alloy a group of researchers studied the alloy in detail to find out the said effect on microstructure and tensile properties. Thermal analysis was carried out with 215–305 °C temperature range to study the microstructure and mechanical properties. Comparative to other third generation Al-Li alloy e.g. AA2099, AA2055 alloy showed remarkable performance in every overaging conditions. AA2055 alloy had specific strength higher than that of AA2099 both in the T83 and harsh overaging condition 24 h at 305 °C [40].

The alloy Al-0.4Cu-0.14Si-0.05Mg-0.2Fe (wt.%) was investigated after adding trace amount of Zr, Ti and Sc to study the microstructure and mechanical properties. It was found that 0.2% Zr additions in base alloy improve mechanical properties of the alloy. Further addition of 0.2%Zr + 0.2%Ti in base alloy refine grain size and if 0.2%Sc was added in 0.2%Zr + 0.2%Ti with base alloy it increases the tensile strength and showed good thermal stability. Again it was seen that if the Sc modified alloy was hold at 350◦C for 200 h it showed remarkable change in tensile strength [41].

Researchers studied alloy (Al–4.5 Cu– 0.3Mg) by adding titanium (0.001–0.5 wt %) to analyze the effect of Ti on tensile properties, microstructure and quality index. It was observed that hot tearing was seen in the alloy which was overcome by 0.05wt% Ti addition. Furthermore, it was found that due to Ti grain sizes were reduced but higher amount of Ti (such as > 0.05 wt% Ti) does not influence the grain size. However, due to addition of Ti ultimate tensile strength (UTS) was improved but it decreases the elongation values. It was seen that by applying T6 treatment it improved quality index, UTS and elongation measurements of the casting. Ductile fracture mode was seen in the analysis for both as-cast and heat-treated conditions. It was noticed that by adding Ti hardness is also increases in both as-cast and heat treated conditions [42].

Literature revealed that 2219 aluminium alloy with 0.8 wt% Sc and 0.45 wt% Mg was developed to study the effect of thermo-mechanical treatments on tensile properties and microstructure of the alloy. The yield strength of the alloy after adding Sc Mg was improved at high temperature (200 °C). Due to generation of $L1_2$ ordered Al_3Sc and $Al_3(Sc, Zr)$ precipitates the 0.2% proof stress was improved for both HMCR and HRCR process. Again, due to Sc and Mg thermal stability of the alloy at elevated temperature is improved [43].

Investigations were carried out to study the corrosion resistance of hypoeutetic Al–Cu alloy and composite fabricated Al–Cu alloy. The amount of Cu in the alloys were Al–5-wt% Cu alloy, Al–10-wt% Cu alloy and Al–5-wt%Cu alloy as matrix and 5-wt% Cu powder which were prepared by stir casting. Corrosion test was perform by taking 5% NaCl solution for time gap (1hr, 2hrs, and upto 8hrs) and varying concentration (e.g. 2.5%) of HCl solution for 2hrs, 4hrs, 6hrs and 8hrs. Results showed that samples in neutral aqueous NaCl solution had better corrosion resistance than aqueous HCl acidic solution [44].

Researchers applied Equal Channel Angular Pressing (ECAP) technique on Al-Cu-Li alloy AA2195 under temperature 250 °C to study the microstructure, texture and mechanical properties. It was noticed that after 4 ECAP passes the grain refinement was seen with average grain size. δ′(Al3Li), β(Al3Zr) and T_1(Al2CuLi) precipitates were found in the alloy. It was seen that the hardness and strength was improved with slight reduction of ductility after 4 ECAP passes [45].

The alloys AA2124 and 25 vol.% SiC reinforced AA2124 were studied to investigate the effect of temperature on wear properties and friction behaviour of the alloys. Dry sliding test revealed that for wear rate and wear mechanism the transition temperature was 100°C. It was seen that aged samples of both the alloys showed increased wear rate with slight abrasive wear when temperature was lower than100°C as compared to non-aged samples of both the alloys. But when temperature was beyond100°C the results were better for aged samples of both the alloys than non-aged samples. Furthermore, wear rates were higher in case of dry sliding situation than lubricated sliding [46].

Researchers studied the consequences of aging temperature on mechanical properties and precipitation phenomenon of AA2519 alloy. Results revealed that long duration of natural ageing improves the ductility and strength of the alloy. This was because of precipitation phenomenon of GP and GPB zones. Same results were seen in case of artificial ageing [47].

Conclusion

The last few decades have witnessed increasing interest to investigate the potential of micro-alloying element in Al-alloys. The motivation for the research is improvement in the properties that can be achieved by micro-alloying elements like Si, Cd, Ti, Sc, Ag, Zn, Zr, In, etc. Even though the scientific interest is promising in nature in this field, there is still a dearth of systematic scientific studies. Several research groups in different countries are working in the area of Al-alloys. In this review paper an overview of research carried out is presented. It is observed that for enhancing the mechanical properties of 2xxx series aluminum alloy, it is important to understand and follow the proper processing steps and also its mechanism behind its strengthening. It is well-known from this review that proper homogenization is the basic important steps before processing of 2xxx series aluminium alloys.

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