Influence of Heat Treatment on Hardness of Heat treatable Aluminum Alloys

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ABSTRACT
In the present investigation, the Heat treatable aluminum alloys of 2014, 6351 and 7075 alloys are subjected to a cyclic heat treatment process: Annealing : Solutionizing: Quenching with different media: Water Quenching, Oil Quenching, Forced Air Cooling, Air Cooling, and Furnace Cooling: and Aging. The Vickers hardness number is taken at every 30 microns location in order to ensure the uniformity of the undergone Heat treatment. It revealed that During the Annealing plus solutionizing cycle the oil quenching resulted in uniform hardness whereas precipitation hardening or aging resulted in much higher i.e., nearly 2-3 times higher than the oil quenched alloy.

Keywords—Heat treatment, Hardness, Solutionizing, precipitation.

I. INTRODUCTION
2xxx series are high strength alloys. The addition of copper as main alloying element (mostly range 3–6 wt. %, but can be much higher), with or without magnesium as alloying constituent (range 0–2 %), allows material strengthening by precipitation hardening, resulting in very strong alloys. Also the fatigue properties are very good for this series. The presence of copper is however very bad for the corrosion resistance. Copper tends to precipitate at grain boundaries, making the metal very susceptible to pitting, intergranular corrosion and stress corrosion. These copper rich zones are more noble/cathodic than the surrounding aluminum matrix and act as preferred sites for corrosion through galvanic coupling. (Learn more in the section on corrosion) Copper is also very bad for anodizing. Copper precipitates dissolve in the anodizing electrolytes (acid electrolytes for porous film formation) leaving holes in the oxide, and solute copper migrates under the high electric field towards the aluminum/oxide interface compromising the anodic film properties.

Up to 12 wt. % copper the strength of the alloy can increase through precipitation hardening, with or without the presence of Mg. Hardening is achieved through the precipitation of Al2Cu or Al2CuMg intermetallic phases during ageing which leads to strengths second only to the highest strength 7xxx series alloys. Above 12 wt. % Cu the alloy becomes brittle. Copper also improves the fatigue properties, the high-temperature properties and the machinability of the alloy. Lower copper content levels then in the conventional 2024 and 2014 type alloys are required for the automotive industry. These alloys have sufficient formability, spot weldability and good corrosion resistance (as opposed to the higher copper containing alloys). The paint baking cycle in the automotive sheet application provides the precipitation treatment and imparts the final mechanical values.

The 2xxx series alloys are used for high strength structural applications such as aircraft fittings and wheels, military vehicles and bridges, forgings for trucks, etc. The low melting phase elements, lead and/or bismuth, facilitate machining of the 2xxx series alloys, making them also suitable for applications where hard extruded and machined parts are required (screws, bolts, fittings, machinery components, etc.).

6xxx series are high strength alloys that can be strengthened by heat treatment (precipitation hardening), through the presence of their main alloying elements silicon and magnesium (mostly in the range 0.3–1.5 wt% Si and Mg). These alloys are generally less strong than the 2xxx and 7xxx series, but have good formability and are weldable. These alloys also have excellent corrosion resistance.

The very good combination of high strength, formability, corrosion resistance and weldability results in
a vast variety of applications for these alloys: transport (automotive outer body-panels, railcars, etc), building (doors, windows, ladders, etc), marine (offshore structures, etc), heating (braze sheet, etc), etc.

Extruded 6xxx series alloys are also often used for machined products; by adding low melting phase elements such as lead, bismuth and/or tin 6xxx series alloys show very good machinability. These alloys can be easily anodised (often hard anodising for extruded parts of brake systems, electronic valves, pistons, etc) where hard surfaces, good corrosion resistance and high strength are required.

For up to 12 % silicon, precipitation hardening of the alloys is possible when silicon is combined with magnesium making the 6xxx series strong alloys. Magnesium and silicon form Mg₂Si precipitates. Furthermore, Si improves the corrosion resistance compared to other alloys except for those of the 1xxx series. Si also improves the fluidity of the molten alloy and reduces the susceptibility to hot crevicing during solidification and heating. More than 13 % Si reduces the machinability.

7xxx series aluminium alloys are high strength, heat treatable alloys containing zinc and magnesium as the main alloying elements. Similar to all heat treatable aluminium alloys, 7xxx series alloys rely on precipitation hardening to improve properties [1]. This series of alloys can be divided into Al-Zn-Mg and Al-Zn-Mg-Cu alloys [2]. AlZn-Mg alloys are relatively weldable and are referred to as medium strength alloys [3]. Al-Zn-Mg-Cu alloys have the highest strength compared to other aluminium alloys. 7xxx series alloys are often used for high strength applications, predominantly in compressively loaded airframe structures [4]. Examples are upper wing panels, frames, stringers, longerons, extruded parts, etc. Other applications include mobile equipment and other highly stressed components. Properties of particular interest for structural applications of 7xxx series alloys are toughness, fatigue crack growth rate, strength, exfoliation and stress corrosion resistance [3, 5].

II. EXPERIMENTAL METHODS

Terminology—
FC-Furnace Cooling
FAC-Forced Air Cooling
AC-Air Cooling
OQ-Oil Quenching
WQ-Water Quenching
VHN-Vickers Hardness Number.

Figure 1: Annealing Cycle for 2XXX, 6XXX & 7XXX Alloys

Full Anneal
Many products are made using the fully recrystallized, fully soft O-temper, often because of formability considerations. The precise annealing practice necessary to achieve this condition for a given alloy is dependent upon the strain, strain rate, temperature of deformation, heating rate, soak time and the annealing temperature itself. However, strain and strain rate, and the temperature of deformation are generally a feature of the fabrication route chosen to give maximum productivity. Variations in the annealing time and temperature (and heating rate to temperature to a lesser extent) are chosen to give the level of recrystallization and hence properties required as shown in figure 1. Full recrystallization is often used on Mg containing alloys where strength is achieved by solid solution strengthening.

Figure 2: Solutionizing Cycle for 2XXX, 6XXX & 7XXX Alloys

Solution heat treatment: the alloy is held at a temperature where in the equilibrium diagram the one-
phase condition is reached as shown in figure 2. The precipitates such as Mg2Si in the 6xxx series and Al2Cu in the 2xxx series are dissolved and the alloy is in the homogeneous solid solution state. The solution treatment temperature is for example for the 6xxx series in the range of 500 – 550 °C, remaining below the melting temperature and avoiding the eutectic temperature.

Figure 3: Solutionizing Cycle & Aging Cycle for 2XXX, 6XXX & 7XXX Alloys

Artificial Ageing

Artificial or natural ageing: the supersaturated one-phase solid solution is not stable below the dissolution line in the equilibrium diagram; this condition has the inherent urge to evolve to a two-phase state. This two-phase state can be achieved in one of two ways:

- Natural ageing at ambient temperature: slowly some precipitates form resulting in a hardness increase that stops after several hours (the final hardness is lower than the hardness obtainable with artificial ageing) as shown in figure 3;
- Artificial ageing: this involves reheating to a temperature below the dissolution line resulting in the more efficient formation or precipitates.

At first the formed precipitates are coherent with the aluminum matrix (i.e. the precipitates still have the same crystalline lattice as the matrix). These coherent phases introduce stresses in the matrix, which are effective barriers against plastic deformation through dislocation movement. Once the precipitates are large enough they become incoherent and form a separate phase; stresses are reduced and the metal becomes softer again, although in any case still harder than the solid state condition due to the stresses inherently present around the precipitates.

Numerical Estimation of Vickers Hardness number

Vickers hardness test requires a diamond pyramid indenter with an included angle of 136°. This technique is also called a diamond pyramid hardness test (DPH) according to the shape of the indenter. To carry on the test, the diamond indenter is pressed on to a prepared metal surface to cause a square-based pyramid indentation as illustrated in figure 4.

\[
VHN = \frac{2P \sin(\theta/2)}{d^2} = \frac{1.854P}{d^2}
\]

Where P is the applied load, kg

\(d\) is the average length of the diagonals \((d_1+d_2)/2\), mm

\(\theta\) is the angle between the opposite faces of the diamond) = 136° generally, the applied load should be carefully selected to achieve a perfect square-based pyramid indentation for accurate hardness values, see figure 5 (a).

The pincushion indentation as shown in figure 5 (b) normally observed in annealed metal results from sinking of metal surrounding the pyramid faces. The measured diagonals would be too long, thus, giving an under-estimated hardness value. In figure 5 (c) a barrel-shaped indentation usually achieved from cold worked metals provides an indentation with metal pile-up at the pyramid faces. In such a case, the measured diagonals would be too small and lead to an over-estimated hardness value obtained. Vickers hardness is widely used in experimental and research areas because the VHN scale practically offers a wide range of hardness values. For instance, the VHN values range from 5 to 1,500 can be obtained from measuring materials from dead soft to full hard. This method is therefore more convenient and provides a wider range of the hardness values in comparison to those obtained from Rockwell and Brinell hardness tests. The applied loads vary from 1-120 kg, which depends on the materials being tested. However, Vickers hardness test is incommomly used for company daily checks. This is due to errors which might occur in the measurement of the diagonals and longer time required to finish the test.
Air Cooling:

Vickers Hardness Number:

\[
VHN = \frac{2P \sin(\theta/2)}{d^2} = \frac{1.854P}{d^2}
\]

<table>
<thead>
<tr>
<th>D1</th>
<th>D2</th>
<th>D=(D1+D2)/2</th>
<th>VHN (Hv)</th>
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<td>40.0207</td>
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<td>40.293</td>
<td>39.5065</td>
<td>39.89975</td>
<td>116.5</td>
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**Table 1:** Hardness values for AA7075-AC

**Graph 1:** Hardness Comparison for AA2014 Alloy

The hardness values for various heat treatments process of AA2014 alloy is shown in the Table 2 & Graph1. It is observed that the furnace cooling during the annealing and solutionizing cycle has very lower value and higher value in the case of Aging i.e., nearly 2-3 times of the furnace cooled value.

**III. RESULTS AND DISCUSSION**

**Hardness for AA6351 Alloy**

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<th>Heat Treatment</th>
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<tr>
<td>Annealing &amp; Solutionizing</td>
<td>FC 43.40, FAC 41.11, AC 42.74, WQ 44.26, OQ 44.05</td>
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<td>Aging Cycle</td>
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</table>

**Graph 2:** Hardness Comparison for AA6351 Alloy

The hardness values for various heat treatments process of AA6351 alloy is shown in the Table 3 & Graph2. It is observed that the furnace cooling during the annealing and solutionizing cycle has very lower value and
higher value in the case of Aging i.e., nearly 2 times of the furnace cooled value.

<table>
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<th>Heat Treatment</th>
<th>Vickers Hardness Number, Hv</th>
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<td>FC</td>
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<td>FAC</td>
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<td>AC</td>
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<td>WQ</td>
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<tr>
<td>Aging Cycle</td>
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</table>

Table 4: Hardness for AA7075 Alloy

Graph 3: Hardness Comparison for AA7075 Alloy

The hardness values for various heat treatments process of AA7075 alloy is shown in the Table 4 & Graph3. It is observed that the furnace cooling during the annealing and solutionizing cycle has very lower value and higher value in the case of Aging i.e., nearly 2 times of the furnace cooled value.

IV. CONCLUSION

The Results shows that for all the materials, AA2014, AA6351 and AA7075, the hardness values are higher for the case for aging next to oil quenching. In annealing and solutionizing The lowest hardness values are found for the furnace cooling. The values of Air cooling, Forced Air cooling does not have much difference as the medium is air itself.

The unique observation during the annealing and solutionizing cycle is that the hardness values are almost uniform over the surface in case of oil quenching which shows the isotropic property when quenched in viscous fluid.

REFERENCES