Effect of Artificial Aging on Strength and Wear Behaviour of Solutionized Aluminium 6061 Alloy

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Abstract: The strength of Al6061 alloy can be improved by precipitation hardening, during the precipitation of metastable phases formed by supersaturated solid solution. The experimental study is focused on artificial ageing of solutionized Al6061 alloy at 100°, 150° and 200° C. The peak hardness is obtained at different aging temperature by plotting hardness v/s time. The peak aging duration is observed to vary between 3 to 10 hours depending on aging temperature. As the aging temperature decreases the precipitation of secondary solute rich phases takes place in the more number of intermediate stages. The intermediate phases strain the lattice during their precipitation to enhance the mechanical properties, so better mechanical property is observed at lower aging temperature. In this paper, mechanical properties such as microhardness, tensile strength, and wear resistance have been studied to determine the effect of artificial ageing on Al6061 alloy. However, under identical heat treatment conditions, the precipitation hardened alloy exhibited better mechanical properties in comparison with as-cast alloy.

Keywords: Al6061 alloy; Artificial aging; Micro hardness; Tensile strength; Wear strength

1. Introduction:
For over five decades, aluminium alloys have attracted attention of many researcher, engineers and designers as promising structural materials for automotive industry or aerospace applications. The heat treatable Al 6061alloys are often chosen for these applications, since they show a good combination of formability, corrosion resistance and weldability as presented by Ohio et al, 1991. In practice only a few elements have been proven to be really suitable as alloying additions in aluminium wrought and cast materials for structural applications. These are: Magnesium (Mg), Silicon (Si), Manganese (Mn), Copper (Cu), Zinc (Zn). They can be used as single elements and also in combinations as described by Chee Fai Tan et al, 2009 and R. Gitteretal, 2008. According to Jastrzebski Z.D, 1959 and S.H. Avner, 1997, the precipitation hardening of aluminium 6061alloy was conducted under different aging temperature with different intervals of time. Precipitation hardening process consists of solutionizing, quenching and aging. Conventionally, in case of monolithic alloys, heat treatment is affected by holding the alloys at a temperature just below the recrystallization temperature (solutionizing) and quenching in a cold medium at room temperature during which the dissolved second phase gets entrapped, forming supersaturated solid solution. It is called precipitation because the small particles of the new phase are termed “precipitates”. Majid Vaseghi et al, 2012 investigated that artificial ageing will be accomplished not only below the equilibrium solvus temperature, but below a meta-stable miscibility gap called Guinier-Preston (GP) zone solvus line. As the conclusion of all the experiments that have been done, the aging has affected the 6061 aluminium alloy in terms of the hardness, tensile strength, wear strength and microstructure behaviour of the specimens.

2. Research on precipitation process on aluminium alloy
The key metallurgical feature of aluminium alloys that may be hardened (strengthened) by heat treatment is complete solute solid solubility at high temperature but only very limited solute solid solubility at roomtemperature. Extensive theoretical and experimental studies have been carried out on the fundamental relationships between the mechanical properties and the microstructure of Al6061 alloy during precipitation hardening process. During the precipitation hardening, the aluminium alloy 6061-T6 was heated up at high temperature and subsequently cooled by quenching it into the water or some other cooling medium. M H Jacobs, 1999 stated that, rapid coolingsuppresses the separation of the θ-phase so that the alloy exists at the low temperature under unstable supersaturated state. If, however, after quenching, the alloy is allowed to ‘age’ for a sufficient of time, the second phase precipitates out. Rafiq A et al, 2000 investigated the mechanical property in under aged, peak aged and over-aged conditions of Al6063 alloy. The variation in time and temperature has improved the mechanical properties of Al alloy with reduction in ductility. Aging at 200° C for 6 hrs, has produced maximum fatigue fracture resistance. Scanning Electron Microscope(SEM) images investigated facet fatigue fracture surface, in under-aged alloys, whereas the peak-aged and over-aged alloy show a mixed mode of fracture, i.e. facet fracture with striation and also inter-granular fracture. J.J. Gracioet al, 2006 investigated the artificial aging behaviour of Al6022-T4 alloy over a wide...
temperature. It was shown that Al 6022-T4 alloy can be substantially hardened through a short aging treatment at temperatures in excess of 200°C in a time interval of less than 2 h. The increase in hardness until the peak-aged condition and finally a decrease in hardness as the specimen becomes over-aged were observed. The under-aged and pre-peak-aged alloy exhibited a good combination of strength and strain hardening while the peak-aged alloy was characterized by maximum strength, although with a drastic reduction in strain hardening ability. The under-aged alloy view that its marginal reduction in strength is counter balanced by an increase in strain hardening ability. G. Mrówka-Nowotnik et al., 2006 investigated the artificial aging behaviour of Al6082 alloy over a wide temperature for different intervals of time. It was found that Al6082 alloy aged at 190°C for 6 h exhibits the best combination of microstructure, mechanical properties and fracture toughness changes during artificial aging due to the precipitation strengthening process. R.A. Siddiqui et al., 2008 investigated the effect of sea water corrosion, aging time, and aging temperature on the fatigue resistance property of Al6063 alloy over a wide temperature for different intervals of time. It was found that alloy aged for 7 to 9 hours and heat treated at temperatures between 160 and 200°C shows best precipitation hardening and has achieved a maximum fatigue resistance property. The results also showed that the brittle fracture pattern tend to occur with the increase in aging time and temperature. F. Ozturket al., 2010 investigated that the solution treatment in the furnace at 500°C for 2 hrs, optimum temperature and duration for peak aged condition was found to be 200°C and 200 minutes to get maximum hardness and yield strength for Al6061 alloy. The presence of intermetallics, change the mechanical behaviour of material like ultimate tensile strength (321 Mpa, which is 73% higher than base alloy) and decreases the strain hardening capabilities. Over-aged condition shows a reduction in the mechanical properties with an increase in aging time and temperature. Majid Vaseghi et al., 2012 investigated the artificial aging behaviour of Al6082 alloy over a wide temperature for different intervals of time. It was found that for achieving the highest hardness value in solution treating, water quenching, and static ageing at 175°C for 3 h and then Equal Channel Angular Pressing (ECAP) at room temperature. According to this schedule, the hardness value increases from 86 HV (as-solution treatment) to 138 HV. Zhao et al., 2005 studied the mechanical properties in ultrafine grained 7075 Al alloy. The highest strength for 7075 Al alloy was obtained by combining the equalchannel-angular pressing (ECAP) and natural ageing processes. The tensile yield strength and ultimate strength of the ECAP processed and naturally aged sample were 103% and 35% respectively, than those of the coarse-grained 7075 Al counterpart. The enhanced strength was produced from high densities of Guinier-Preston (G-P) zones and dislocations. The study showed that severe plastic deformation has potential to enhance the mechanical properties of precipitate hardening 7000 series Al alloys significantly. Kulkarni et al., 2004 investigated the effect of particle size distribution on strength of precipitation-hardened alloys. Ageing of precipitation hardened alloys results in particle coarsening, which in turn affects the strength. In this study, the effect of particle size distribution on the strength of precipitation hardened alloys was considered, to better represent real alloys, the particle radii were distributed using Wangner and Lifshitz and Slyozov (WLS) particle size distribution theory.

3. Experimental method

The base matrix chosen in the present study is the aluminium 6061 because it is one of the most extensively used 6000 series aluminium alloys. They have high strength to weight ratio, good formability, age hardenability and other appropriate properties. Among different aluminium alloys, Al 6061 has high machinability, high hardness property and also light weight. Table 1 gives the chemical composition of Al6061. The cast specimens were cut to dimensions to prepare the samples for Hardness, Tensile and Wear tests. All specimens are solution-treated at 550°C for 2 hours, then immediately quenched in water at room temperature and then specimens were artificially aged in the furnace at 100°C, 150°C and 200°C for various durations of time (T6 treatment). Figure 1, represents the heat aging treatment cycle. Hardness values were measured first at different time intervals to find the peak aging time for a particular temperature. For this peak aging time tensile and wear tests were conducted.

Table 1: Nominal composition weight percent of Al-6061 matrix material

<table>
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<tr>
<th>Material</th>
<th>Si</th>
<th>Fe</th>
<th>Cu</th>
<th>Mn</th>
<th>Zn</th>
<th>Ti</th>
<th>Mg</th>
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<td>0.7</td>
<td>0.1</td>
<td>0.5</td>
<td>0.4</td>
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**Figure 1** Age hardening treatment of Al 6061 alloy
Vickers Hardness test were conducted and average of at least six indentations are taken at room temperature. Hardness measurements were performed using a Vickers hardness tester (MATZUSAWA MICRO VICKERS HARDNESS TESTER, MODEL-MMT X 7A) with a load of 100 gmf and dwell time of 15 seconds was given. The cylindrical specimens of 12mm diameter and length 15mm were used for the test. Before testing the specimen surface was polished in metcobainpol polishing machine using diamond paste abrasives.

The tensile strength tests were performed on Electronic tensometer (model-ER3) as per ASTM-E8M standard for as-cast, as quenched and peak hardened condition. Circular cross section specimen was prepared with diameter 6 mm and gauge length 24mm. The load cell value was kept to 20.5 kN and test mode was selected as break. The cross head speed was kept constant at 12 mm/ min, with length increment value of 0.01 mm.

The Wear resistance tests were performed on pin-on-disc tribo-meter under dry sliding conditions (WEAR AND FRICTION MONITOR TR- 201CL). The test were conducted on 8 mm diameter, 25 mm long cylindrical specimens (ASTM G-99) against a rotating EN-32 steel disc (count face) having hardness 63Rc. Care should be taken to note that the test sample’s end surfaces were flat and polished metallo-graphically prior to testing. Conventional aluminium alloy polishing techniques were used to get ready the contact surfaces of the monolithic aluminium specimen for wear test. The procedure involves grinding of aluminium surfaces manually by 240, 320, 400, and 600 grit silicon carbide papers and Fine polishing was done in a rotating disc polishing machine with velvet cloth impregnated with diamond paste. The track diameter was kept constant at 60mm. The test was conducted for three different loads (15 N, 30 N and 45 N). For each load the speed was varied (150 rpm, 300 rpm and 450 rpm). Initial weight of the sample was noted down. For a particular load at a particular speed the test was run for 1 hr. At an interval of 15 minutes the weight loss was noted by weighing the sample.

4. Results and discussions
4.1 Hardness
Higher the aging temperature lower is the peak hardness. The peak hardness is observed in lesser duration compared to lower aging condition. But higher peak hardness value is observed at lower aging temperature. This increase in the peak hardness is due to the secondary precipitation of intermetallic phases with number of intermediate stages. During the formation of intermediate phases, the matrix lattice is strained, which increases the peak hardness value. Lower aging temperature also increase the nucleation sites, accordingly more number of precipitates are formed at such nucleation sites and dislocation mobility is locked up by these particles also contribute to the increased hardness and wear resistance. The higher hardness may be due to the formation of well distributed finer solute rich intermetallic phases. The finer precipitates not only increase the hardness but also strengthen the matrix with higher toughness. In all the aging temperatures the peak hardness is observed in significant durations as shown in Figure 2.

![Figure 2: Variation of VHN of samples aged at 100°C, 150°C and 200°C with respect to time.](image)

4.2 Tensile test
Tensile strength of the solutionized specimen shows lower value compared to the aged specimen. Solutionized specimen show higher ductility compared to the aged specimens. Since area under the stress-strain diagram is the indication of toughness, the higher temperature aged and solutionized specimen show higher toughness. Solutionizing results in single phase FCC aluminium rich supersaturated solid solution which exhibit higher ductility. The fractured surface also shows a clear ductile failure. As the aging temperature decreases, tensile strength of the material increases with the reduction in toughness and ductility. The as-cast specimen show neither higher strength nor toughness. This may be due to the continuous network of solute rich brittle phase along the grain boundary. If the aging process is designed properly, the strength of the material increases. This may be due to the fine distribution of secondary precipitates in the aluminium rich solid solution matrix. Lower the aging temperature higher is the tensile strength. This is due to straining the matrix during the precipitation of inter-metallics with number of intermediate metastable stages. The tensile behavior of all, treated and untreated specimens are shown in the Figure 3. The fractured surface of the peak aged specimen at lower aging temperature shows partial ductile and brittle failure.

![Figure 3: Engineering Stress-Strain graph of as-cast solutionized and precipitation hardened Al 6061 specimens.](image)
4.3 Wear resistance test

The dry sliding wear behaviour of the alloy is analysed. At constant rpm of the disc, the wear rate versus sliding distance graphs are drawn at different pin loads (15N, 30N and 45N). In all the load conditions as the sliding distance increases wear rate decreases after the initial severe wear. Severe wear mode is observed in all the load conditions upto 3.4 kms of sliding distance. At 15N load conditions, where the load on the pin is very small the wear rate is almost maintained constant in all the aging conditions at higher sliding distances, but sensitive at lower sliding distance. This may be due to the rough contacting surface of specimen during the initial period of run. As the load on the pin increases the wear rate decreases with increase in sliding distance. This is due to the strain hardening phenomena. At lower loads the intensity of strain hardening are small, accordingly the wear rate is not so sensitivewith sliding distance and aging conditions. But appreciable changes are observed at higher loads. Higher the load, strain hardening is also higher, thus wear rate is lower. But higher the aging temperature higher is the wear rate. At higher aging temperature coarser the grain, lesser is the hardness or higher is the wear rate and lesser number of intermediate zones in the formation of coherent precipitates that is lesser is the strain on the matrix. On the other hand lower aging results in more number of intermediate zones, more is the coherent strain in the lattices with the precipitation of finer intermetallics. Higher load and higher sliding distance condition imparts severe strain hardening, hence wear rate decreases. This phenomenon is clearly observed in wearrate curves as shown in Figure 4 (a,b & c) at different load conditions.

Figure 4 Wear rate v/s sliding distance of As-cast and peak aged Al 6061 alloy at 
(a)15N (b) 30N (c) 45N

(A) (B) (C)
As the rpm increases, in all the aging conditions wear resistance increases as the load on the pin increases. This increased wear resistance is clearly observed at higher rpm instead of lower rpm. The result could have been still better if the load on the pin would have been increased beyond 45N. Even for constant sliding distance as-cast and higher aging temperature specimens show higher wear rate compared to lower aging temperature. This trend is clearly observed in Figure 5 (a,b & c). So strain hardening and well distributed finer precipitates in the matrix with more number of intermediate stages during the precipitation contributes towards increased wear resistance.

4.4 Scanning Electron Microscope (SEM) Analysis

The SEM micrographs of the Al6061 alloy in the peak aged condition at 200°C and 100°C are shown in the Figure 6. At 200°C lesser number of precipitates is observed and majority of them are concentrated at the grain boundary. At 100°C the precipitates (intermetallics) are observed along the grain boundary as well as inside the grain. More number of evenly dispersed precipitate are observed at lower aging temperature compared to higher aging temperature. At the same time finer grains are observed at lower aging temperature. The finer grains, homogeneously distributed large number of finer secondary phases and closer inter-particle distances are responsible for higher strength and hardness of the specimen at lower aging temperature. Micro analysis result also matches with the chemical composition of the alloy under consideration by EDAX analysis as shown in Figure 7. The SEM and EDAX analysis records the precipitation of finer Mg2Si intermetallics along the grain boundary as well as within the grain condition at lower temperature aging.
Conclusion

- The Al6061 alloy positively responds for age hardening treatment. There is improvement in hardness, strength and wear resistance of the alloy, if the treatment is tailored efficiently.
- In all the aging conditions peak hardness is observed in significant durations with the two fold increase in the hardness value at lower aging temperatures.
- The wear resistance is better at higher sliding distances and higher loads. Surprisingly higher rpm of the disc also contributes to the increased wear resistance.
- Higher the aging temperature lower is the strength of the peak aged specimen with increased toughness.
- SEM micrographs at lower aging temperature records the precipitation of large number of evenly distributed intermetallics (Mg,Si) within and along the grain boundary as finer precipitates.

References:


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