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Improving the Productivity and Energy Efficiency by a Heat Treatment Method Applied to Aluminum Forged Parts

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Abstract

In industrial applications, hot forging of AA6082 alloy is carried at 480°C. After the hot forging operation parts are cooled down to room temperature and heated again up to 540°C for solution heat treatment and artificially aged. Heating-cooling-heating cycles leads to energy and time loss in production, and have long-term environmental and economic impacts. Mass production of aluminum parts for applications in various industries (automotive, aerospace etc.) requires a process with higher productivity.
The aim of this study was to provide time and energy efficiency by combining hot forging and solution treatment processes into a single operation. AA6082 billets were forged at 540°C for 7.5, 15 and 30 minutes in order to achieve simultaneous solution treatment. Billets were then water quenched and artificially aged. Mechanical properties (hardness, tensile strength) as well as microstructure of samples were investigated. Required mechanical properties were achieved on the samples forged and treated at 540°C for 15 and 30 minutes.

Keywords: Energy Efficiency, Aluminum, Forging, Heat Treatment, Process Improvement

Introduction

Owing to desirable properties such as high corrosion resistance, formability (forging, extrusion etc.), machinability and high strength, AA 6082 aluminum alloy have various applications in machine, aerospace and automotive industries [1]. Most common heat treatment applied to AA 6082 is T6 (solution heat treatment and artificial aging).

Hot forging entails the heating of a work piece to about 75% of its melting temperature. This allows for the flow stress and energy required to form the metal to lower, effectively increasing the rate of production (or strain rate). Hot forging aids in making the metal easier to shape as well as less likely to fracture. While other materials need to be strengthened through the forging process itself, materials such as most of the titanium and aluminum alloys, can be hot forged and then then hardened. Forging temperature for AA 6082 alloy is between 450-500 °C [2]. Induction heaters are commonly used to heat parts up to hot forging temperatures. The forged parts are then cooled down to room temperature, heated up again to apply conventional solution treatment followed by quenching and artificial aging processes. Repetitive heating/cooling steps are a significant cause of energy loss.

Several studies examined the effects of different aging and heat treatment processes on the microstructure and mechanical properties of AA6082 parts. Other studies have examined the possibility to replace rolled or extruded parts with cast ones. These studies were focused on the employability of AA6082 parts as-cast or after homogenization heat treatment [2-7]. There are few details about the microstructure and mechanical properties of the AA 6082 aluminum alloy with or without deformation after short-term heating by induction. Literature review also revealed that there is very little information available about the T5 heat treatment of aluminum alloy AA 6082. Existing studies examined the properties of these alloys with small number of variables and consist of limited information. In this context, an experimental work at a predefined heating time of 15 minutes was carried out by Zvinys et al. Primary importance of this study is the investigation of optimum forging temperatures to obtain the right solution temperature [3]. There was not any detailed information about the conditions of forging and heat treatment presented in TALAT aluminum heat treatment programs [2].

In this study, AA 6082 alloy were water quenched immediately after forging at 540 °C and then aged for 8 hours at 180 °C to combine hot forging and solution treatment processes in a single high-temperature process. This heat treatment pattern is quite similar to T5 applied to aluminum alloys.

Experimental

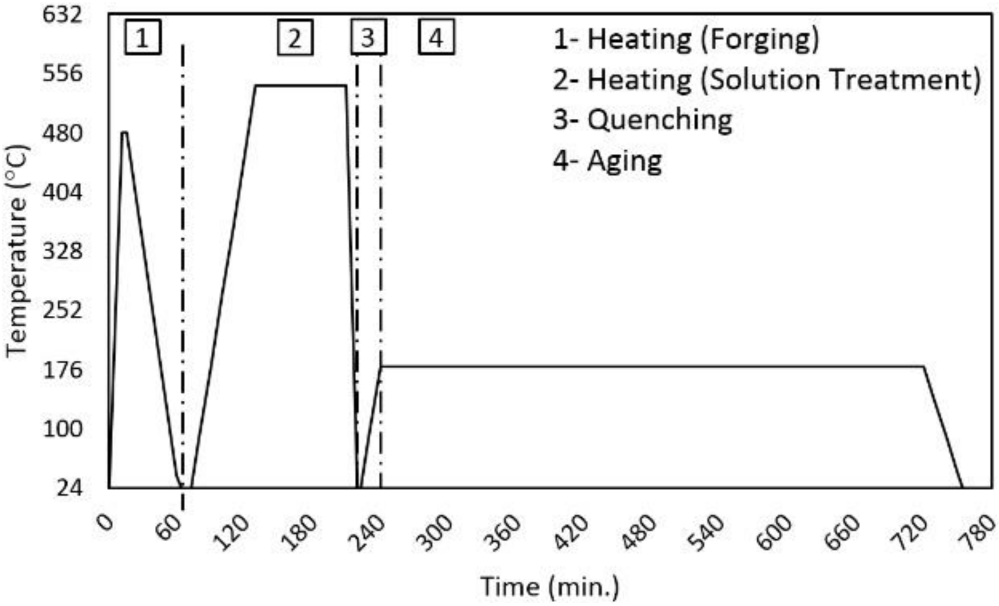
AA6082 alloy bars (36 mm diameter, 85 mm length) supplied by ASAS Aluminum were used in this experimental work. Bars had nominal chemical composition (Table 1) and 47-52 HB hardness. AA 6082 alloy contains Si, Mg, Mn and Fe and a mid-high strength alloy that is commonly used as extruded and forged aluminum products. Strengthening mechanism is the precipitation of Mg-Si-Mn intermetallic compounds (especially Mg_2Si). A common acceptance criterion for this alloy in the industry is a hardness value of 90 HB.

Table 1. Nominal chemical composition of alloy AA 6082 and chemical composition of AA 6082 bars used in present study.

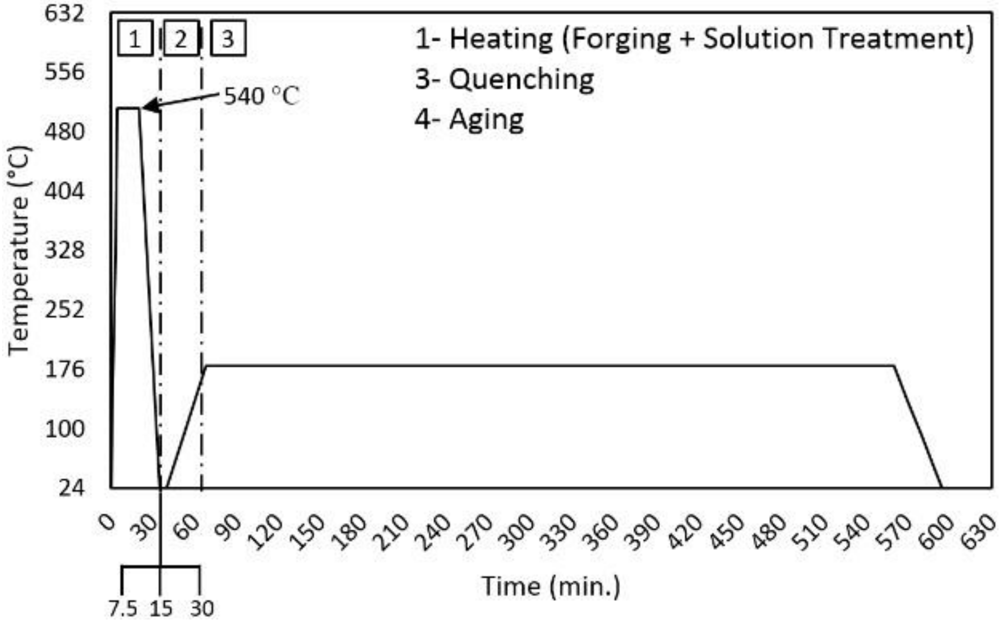
Element	Nominal (wt. %)	Present (wt. %)
Si	0,70-1,30	1,00
Mg	0,60-1,20	0,66
Mn	0,40-1,00	0,42
Fe	Max. 0,50	0,23
Cr	Max. 0,25	0,10
Zn	Max. 0,20	0,01
Cu	Max. 0,10	0,01
Ti	Max. 0,10	0,02
Other	0,05-0,15	0,06
Al	Remaining	Remaining

Conventional T6 heat treatment pattern of AA 6082 alloy is illustrated in Figure 1a. In this pattern, parts are cooled down to room temperature after hot forging, heated up again to a suitable solution heat treatment temperature, quenched to room temperature and artificially aged to obtain required hardness values depending on the application. In this study, second step (2) of this pattern was eliminated from the process to obtain the improved heat treatment illustrated in Figure 1b.

This new pattern was expected to provide a higher time and energy efficiency. Solution treatment and hot forging were carried out simultaneously at 540 °C, which is the conventional solution heat treatment temperature. Various process durations (7.5, 15 and 30 minutes) were applied in order to find an optimum temperature-time combination. Following this combined pattern, aluminum bars were artificially aged for 8 hours at 180°C. Total process time was at least 2 hours shorter. Two distinct groups of samples, without deformation and with 10% deformation were investigated in this study.



(a)



(b)

Figure 1. Heat treatment patterns (a) conventional T6 process and (b) experimental process.

The detailed work flowchart followed is given in Figure 2. Sample denomination is shown in Table 2.

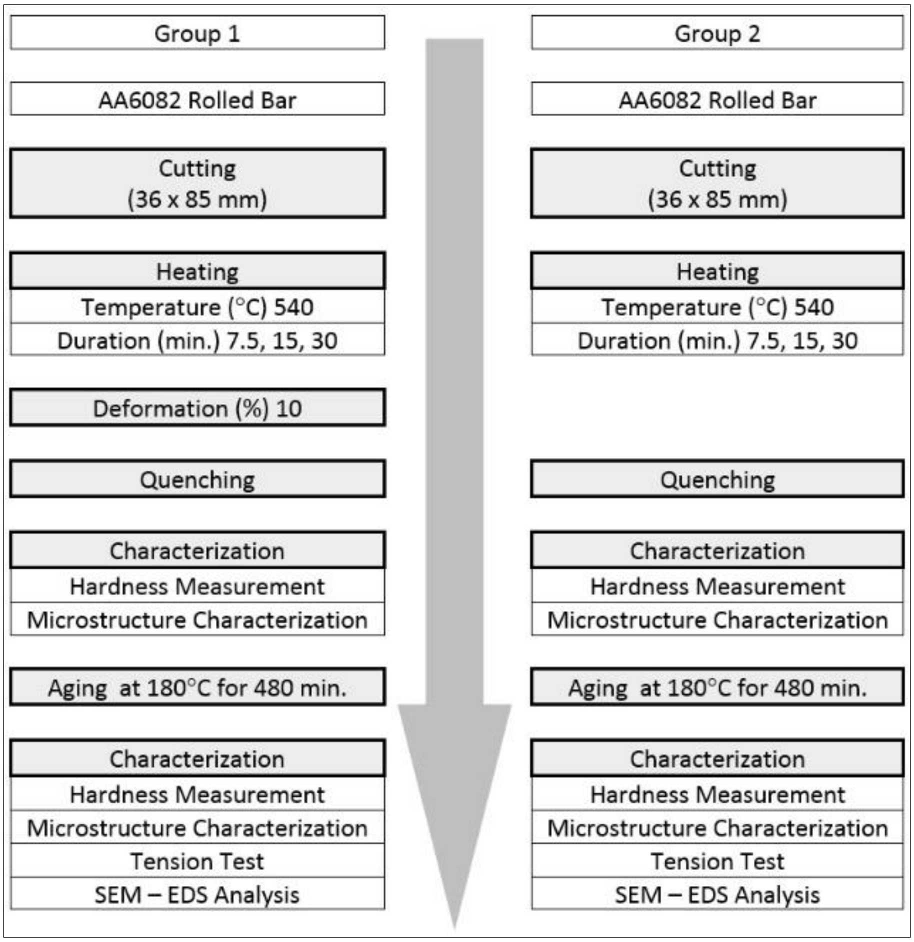


Figure 2. Experimental process flow chart for two sample groups.

Table 2. Sample denomination.

Group No.	Sample No.	Process Temp. (°C)	Process Time (min.)	Deformation (%)
	A1	540	7.5	10
1	A2	540	15	10
	A3	540	30	10
	A4	540	7.5	0
2	A5	540	15	0
	A6	540	30	0

Group 1 samples (samples A1, A2 and A3) were prepared by cutting a cylindrical bar, heat treating 540 °C for 7.5, 15 and 30 minutes and then introducing 10 % plastic deformation prior to quenching into water bath (Figure 3). An automatic 5-ton vertical hot forging ram was used. Group 2 samples (samples A4, A5 and A6) were also heat treated at 540 °C for 7.5, 15 and 30 minutes and directly quenched to water bath without introducing any deformation. All the samples were artificially aged at 180 °C for 8 hours.

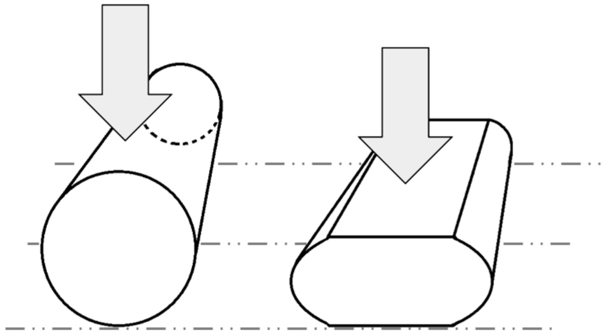


Figure 3. Illustration of plastic deformation introduced to Group 1 samples by hot forging.

All samples were characterized before and after the aging process. Figure 4 illustrates the regions from where specimens were taken.

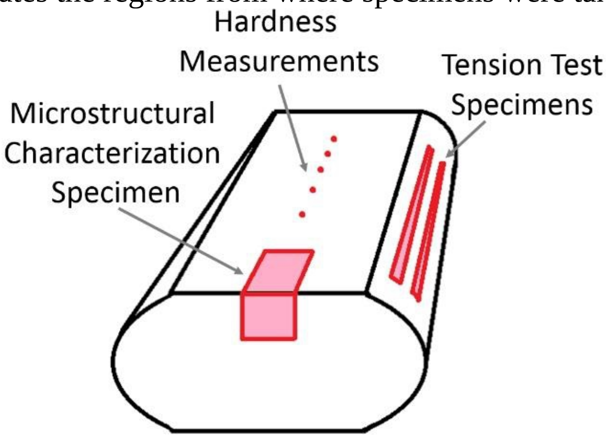


Figure 4. Illustration of the regions on Group 1 samples used to obtain experimental data.

Brinell hardness measurements (750 kg load, 5mm ball indenter, polished surface) and standard tension tests were carried out using Emcotest M5C030G3 Hardness Tester and Zwick Tensile Testing Instrument. Tension test specimens were prepared according to the DIN 50125 standard. Tensile strength and % elongation values of Group 1 and 2 samples were calculated before and after the aging process.

Microstructure characterization samples were chosen from the region exposed to the most severe deformation in a way to reveal the structural change from the surface. Samples were ground using SiC abrasive papers, diamond polished and chemically etched using NaOH solution. Nikon Eclipse Optical Microscope (OM), Philips XL 30 FEG Scanning Electron Microscope (SEM) and integrated EDAX Energy Dispersive X-ray Spectral Analysis (EDS) system were used for microstructural characterization and elemental analysis. Elemental analysis was carried out from the aluminum matrix and precipitates in the microstructure.

Results and Discussion

Mechanical properties and microstructures of specimens - heat treated and hot forged for various durations (7.5, 15 and 30 minutes) - were compared before and after artificial aging. Hardness test results, calculated as the average of 5 measurements on each sample, are given in Table 3.

Table 3. Hardness test results.

Sample No.	Hardness before aging (HB)	Hardness after aging (HB)
A1	81	84
A2	88	106
A3	90	112
A4	77	82
A5	84	102
A6	88	108

Hardness values of Group 1 and 2 specimens were between 81-88 HB before and 84-108 HB after artificial aging process (at 180 °C for 480 min). Figure 5 and 6 gives the variation of hardness values depending on process duration and deformation before and after the aging process.

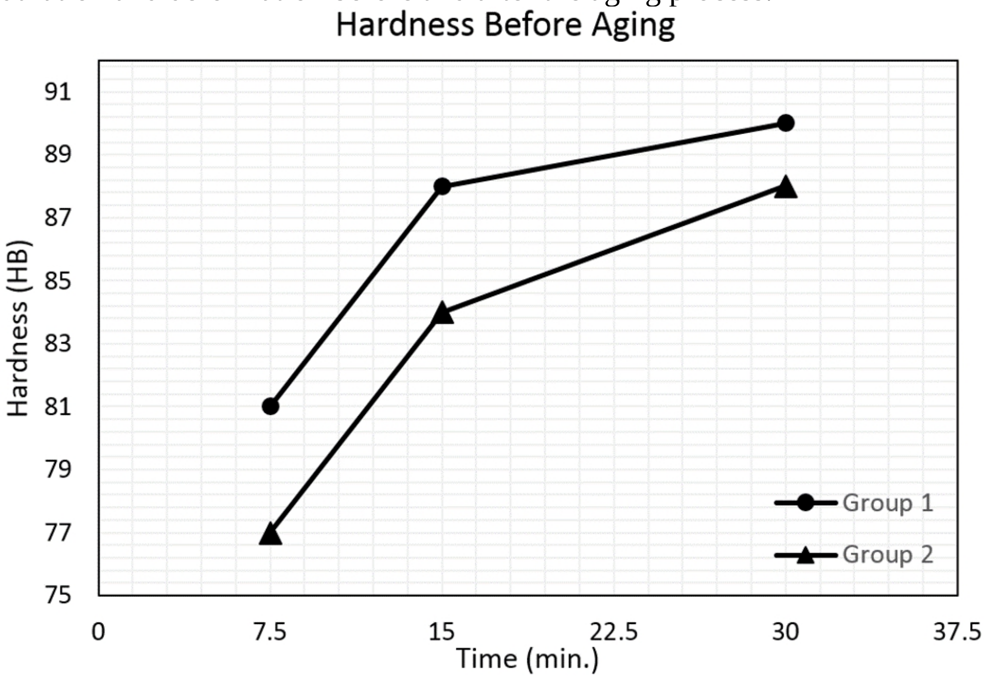


Figure 5. Variation of hardness values depending on heat treatment time - before artificial aging

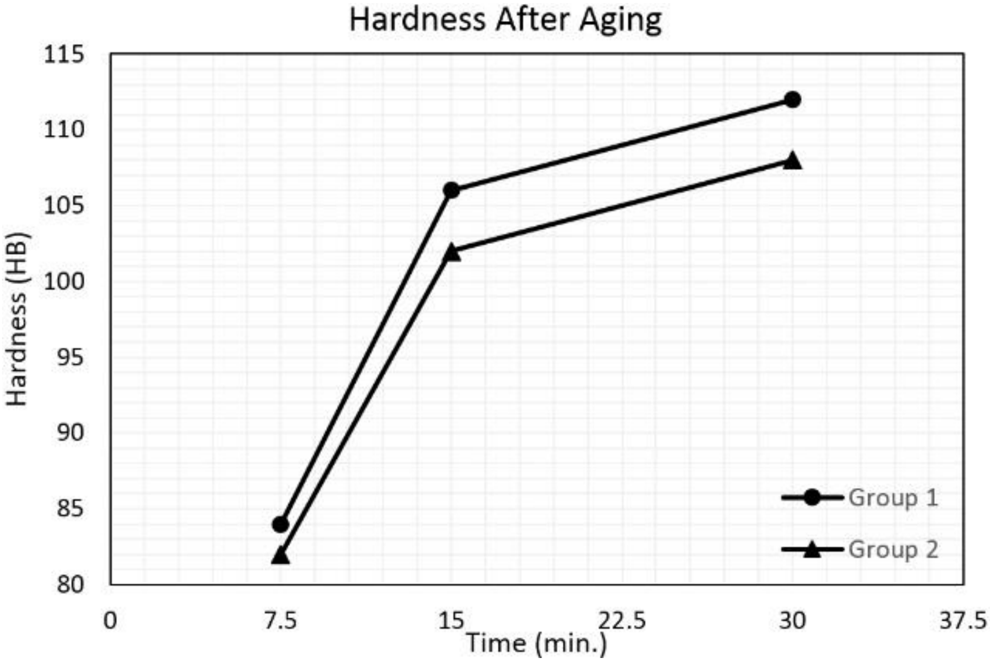


Figure 6. Variation of hardness values depending on heat treatment time - after artificial aging

It is evident that the quenched hardness of the samples significantly increased depending on increasing solution treatment temperature. It was also observed that plastic deformation did not have any notable effect on the Brinell hardness values of the two sample groups. Thus, microstructural characterization was only carried out for Group 1 samples.

Table 4 gives the yield strength, tensile strength, and elongation values of aged samples.

Table 4. Tension test results.

Sample #	Yield strength (N/mm^2) Min 260 N/mm^2	Tensile strength (N/mm^2) Min 310 N/mm^2	Elongation (%) Min. %6
A1	-	228.16	21.1
A2	290.33	344.72	18.47
A3	315.38	372.63	15.95
A4	-	208.13	21.05
A5	288.34	338.21	18.12
A6	305.83	362.02	16.85

Tensile strength and % elongation values of the specimens were within the range of 228-362 N/mm^2 and 21-17 % respectively.

Tensile strength of the samples increased depending on increasing process duration, showing a similar tendency to the hardness (Figure 7). Deformation did not have any influence on the tensile strength of the samples.

The wide range in elongation and strength values can be attributed to the non-homogeneous distribution of precipitation phases. When process time is short, due to limited diffusion, insufficient amount of quantity of coherent and semi coherent precipitation can occur within the alloy [8].

Tensile strength values of the samples treated for 7.5 minutes below whereas the tensile strength of the samples treated for 15 and 30 minutes were above the desired value. Elongation values tend to decrease with increasing tensile strength. Both hardness and tensile strength of the samples increased after aging.

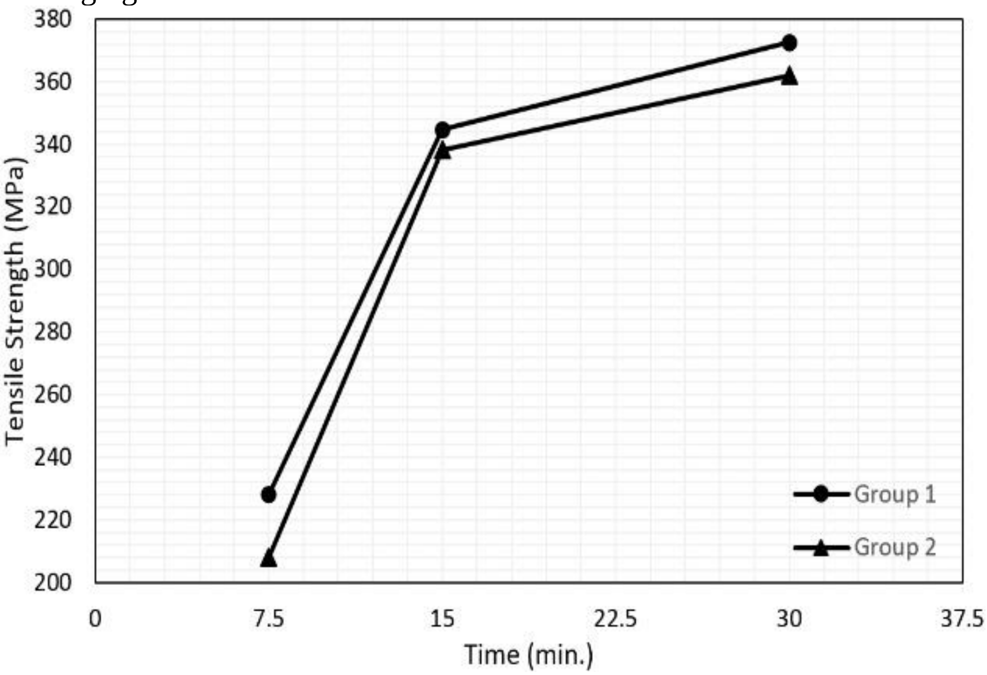


Figure 7. Tensile strength of Group 1 and 2 samples - heat treated 7.5, 15 and 30 minutes and artificially aged.

For industrial applications (machine components etc.) acceptance criteria for AA 6082 alloy is that the hardness of the part must be over 90 HB. Experimental results showed that for short process durations hardness values were below the desired value, most probably due to the insufficient amount of dissolved second phase. After artificial aging, hardness of the samples treated for 15 and 30 minutes were over 90 HB (Table 3).

Optical microscope images of the samples Group 2 samples before and after artificial aging are given in Figure 8.

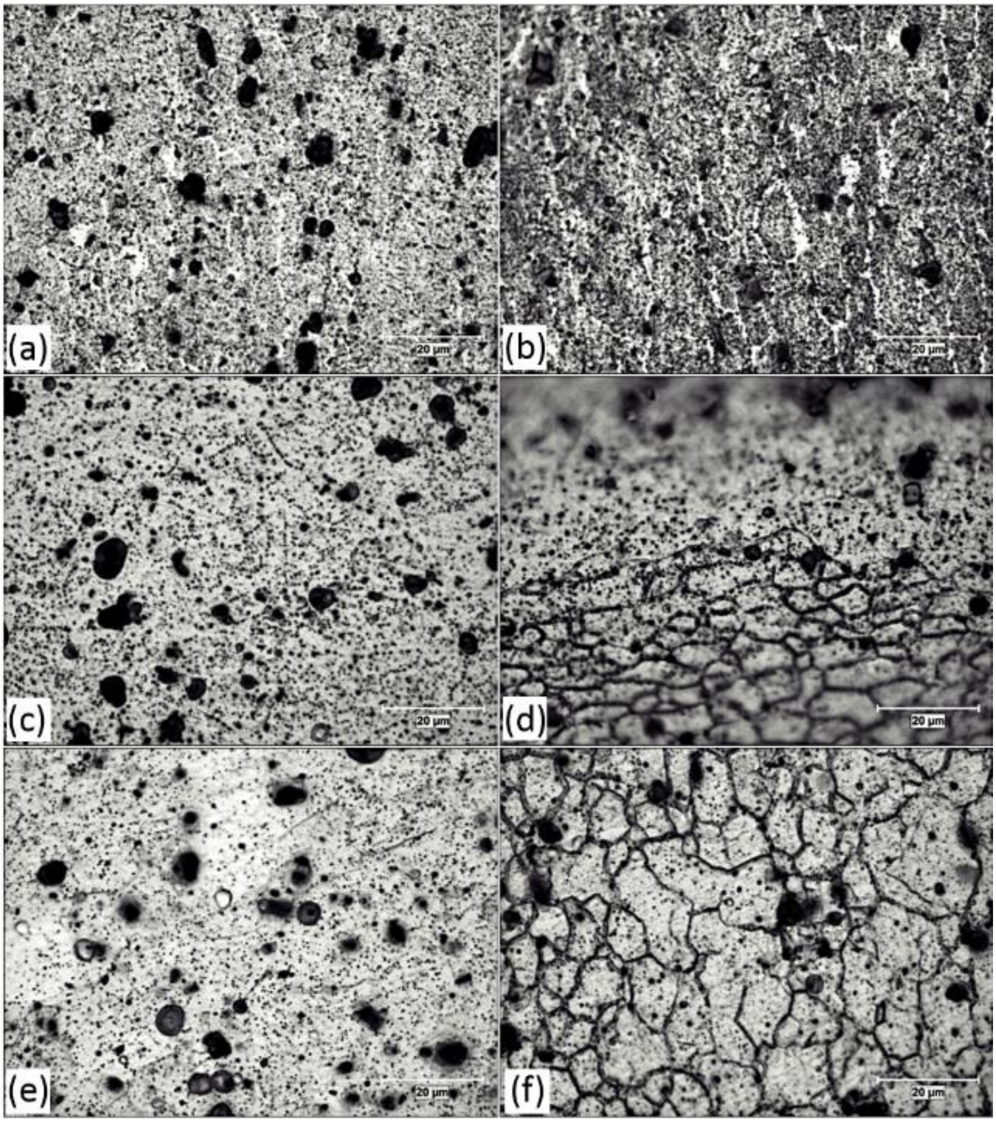


Figure 8. Optical microscope images (a) sample A4 (b) sample A4-aged (c) sample A5 (d) sample A5-aged (e) sample A6 and (f) sample A6-aged.

Comparison of microstructures given in Figure 8 reveals that the artificial aging process alters the alloy microstructure. Grain growth occurred from surface towards the center during artificial aging. Figure 8b shows the transition between the coarse surface and fine inner region. Considering the deformation is concentrated on the surface during forging, it is clear that the aging process acted as a partial recrystallization anneal. It can be observed that second phase precipitates are finer and distributed more homogeneously within the structure after artificial aging process, depending on process duration. Coarse precipitates at low solution treatment temperatures are dissolved and spread over the matrix with finer precipitation as the process temperature increase.

SEM micrograph of the AA6082 alloy is given in Figure 9. EDS analysis results of various regions marked on Figure 10 are given in Table 5.

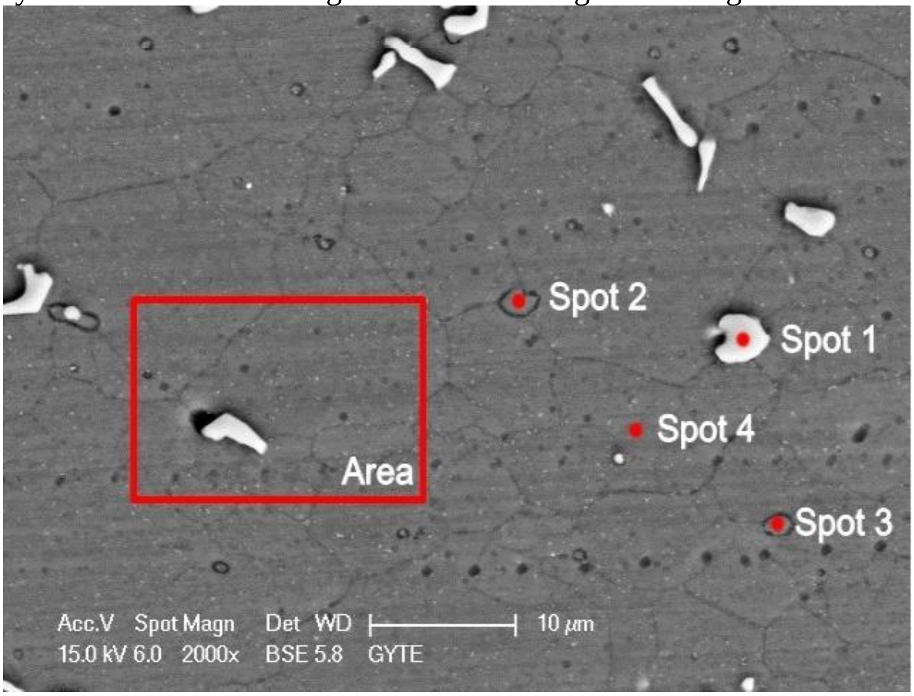


Figure 9. SEM micrograph of AA6082 alloy. EDS analysis regions are marked.

Figure 9 shows that coarse precipitates in the alloy has no regular geometry. Very thin and light gray colored spherical precipitates are also present. Grain boundaries and fine precipitates which are the result of the aging process are also visible.

Table 5. EDS analysis results.

Region	Element (wt. %)				
	O	Mg	Si	Mn	Al
Spot 1	1.51	0.52	11.93	14.35	71.68
Spot 2	3.4	9.47	7.32	-	79.8
Spot 3	6.6	21.05	16.1	-	56.25
Spot 4	1.23	1.99	1.33	-	95.46
Area	-	1.56	1.52	-	96.52

EDS results show that irregular bright precipitates (Spot 1) consist of Al, Mn, Si and Mg whereas light grey precipitates (Spot 2 and 3) consist of Al as well as high amount of Si and Mg. Spot 4 is the matrix alloy. Considering these results and earlier studies on alloy AA 6082, it can be concluded that these precipitates are complex binary and/or ternary intermetallic compounds such as Mg_2Si, $Al_{10}SiMn_3$ and $Al_{15}Si_2Mn_3$ [8]. Precipitation of second phase particles during heat treatment is the main strengthening mechanism of AA6082 alloy. Above the solvus line, solubility of Mg and Si in Al increases depending on the treatment temperature. Quenching creates a super saturated matrix and after artificial aging, precipitates formed through the super saturated Al matrix retard the dislocation motion and increase the mechanical strength and the hardness values. This increment tends to be higher for higher concentration of Mg and Si in solid solution.

Conclusion

Experimental results are summarized below:

1. Deformation had a slight effect on hardness, elongation and strength values.
2. Hardness and tensile strength values of the samples increased with increasing heat treatment duration.
3. Samples did not reach the sufficient hardness before aging. All samples, except the ones treated for 7.5 minutes, had sufficient hardness (over 90 HB) after artificial aging.
4. A fine grain structure was observed through the inner regions of aged samples. Recrystallization and grain growth occurred after ageing depending on increasing process duration.
5. Al, Si, Mg and Mn elements were observed within the precipitates in the matrix phase. Complex intermetallic compounds were formed through the matrix.
6. Induction heating is employed for pre-heating of forging parts for a very short term in the industry. Results of this study revealed that short heating durations at elevated forging temperatures of AA6082 alloys are sufficient to obtain the required hardness values.
7. Simultaneous hot forging – solution treatment process provided time and energy efficiency for AA 6082 aluminum forged parts.

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