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Effect of Artificial Aging on the Mechanical Properties of an Aerospace Aluminum Alloy 2024

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Abstract. Aluminum alloys have low specific weight, relatively high strength and high corrosion resistance and are used in many applications. Aluminum Alloy 2024 is widely used for aircraft fuselage structures, owing to its mechanical properties. In this investigation, Aluminum Alloy 2024 was given solid solution treatments at 495, 505, and 515°C followed by quenching in water. It was then artificially aged at 190 and 208°C. Subsequently, hardness measurements, tensile tests as well as impact and fatigue tests were carried out on the heat treated alloys to determine the mechanical properties. The tensile and hardness tests revealed similar mechanical properties for specimens of this alloy that were given the three solid solution treatments. Aluminum Alloy 2024 specimens that were solid solution treated at 515°C and artificially aged at 208°C for 2h exhibited the highest yield and tensile strength. In general, the increase in strength was accompanied by a decrease in ductility. Cyclic fatigue studies were conducted with symmetric tension-compression stresses at room temperature, using a bending-rotation test machine. The alloy solution heat treated at 515°C and aged at 208°C/2h was fatigue tested at constant frequency. The relation between stress amplitude and cycles to failure was established, enabling the fatigue strength to be predicted at more than 7.8×10^6 cycles, with maximum stress of 110.23 MPa. The fracture surfaces of specimens that failed after fewer cycles showed mainly precipitates and micro voids, whereas specimens that fractured after a higher number of cycles indicated that cracks initiated at the surface. The high cycle fatigue fracture surfaces revealed pores that could be due to precipitates from the matrix.

Introduction

Aluminum alloys are replacing steels in applications where lower weight and reduced maintenance costs are requisites. Structural materials require not only high strength/weight ratio, besides reasonable cost, but high fatigue resistance. Precipitation strengthening is an important hardening method and is used to increase the strength of some aluminum alloys [1-3]. In precipitation strengthening, the second phase precipitates within the matrix phase. However, in 2xxx aluminum alloys, fatigue crack propagation resistance decreases with artificial ageing. The fatigue behavior of artificially aged 2xxx alloys is largely unknown, whereas the fatigue behavior of naturally aged 2xxx aluminum alloys has been studied [4-9].

Aluminum Alloy 2024 (AA 2024) is an aluminum alloy containing copper, magnesium, manganese and some minor alloying elements. Among the various aluminum alloys, AA 2024 has the highest hardness and it is used in the manufacture of airplanes. An important aspect of Aluminum Alloy 2024 is that the solid solution treatment is not critical. This alloy can be aged naturally or artificially. The main precipitation-hardening reactions are those related to the ternary aluminum–copper–magnesium system. Commercially important Al alloys contain copper as the main alloying element and phase reactions that occur are those between the aluminum solid solution and the intermetallic phases $CuAl_2$ and $CuMgAl_2$.

We chose to study this aluminum alloy because of its importance in the aerospace industry and the fact that its strength can be increased considerably by precipitation that takes place during solid solution treatment and aging. The purpose of this investigation was to study the mechanical properties (tensile, fatigue and hardness) of solid solution treated and aged Aluminum Alloy 2024. Fatigue tests were performed with tensile stress cycles to obtain an S-N curve. The fracture mechanisms were evaluated with the aid of scanning electron microscopy.

Experimental

Table 1 shows the chemical composition of Aluminum Alloy 2024 used in this investigation. The solid solution treatments were carried out at 495, 505 and 515°C for one hour followed by quenching in water. Artificial aging was carried out at 190 and 208°C, for periods ranging from 30 minutes to 48 h. The Brinell hardness of samples, both in the solution treated as well as in the solution treated and aged conditions were determined. These measurements were carried out in quintuplicate. The samples for optical microscopic examination were prepared using conventional metallographic techniques such as polishing and chemical etching with HBF_4.

Table 1: Chemical composition of 2024 aluminum alloy.

Element	Mg [%]	Si [%]	Mn [%]	Cu [%]	Zn [%]	Fe [%]	Ti [%]	Cr [%]
Content	1.47	0.07	0.64	4.58	0.07	0.17	0.03	0.005

Tensile tests were performed in triplicate for each heat treatment condition. Tensile tests were carried out to determine the yield stress at 0.2% plastic strain, ultimate tensile strength and total elongation. Fatigue tests were performed in a bending-torsion machine. Fatigue tests were carried out on samples that had been solid solution treated at 505°C and artificially aged at 208°C/2h. The results of the fatigue tests were plotted to obtain the S-N curve. The fracture surfaces of samples that were tensile and fatigue tested were observed in a scanning electron microscope.

Results and Discussion

Figure 1 shows a typical optical micrograph of Aluminum Alloy 2024 solid solution treated for 1 hour and quenched in water. An important feature of this micrograph is elongated grains as a result of rolling. Optical microscopy did not reveal major differences in the microstructure of samples that were solid solution treated at 495, 505 and 515°C. Table 2 shows the Brinell hardness (HB) of Aluminum Alloy 2024 that was solid solution treated at 495, 505 and 515°C for 1 hour followed by quenching in water and ageing at 190 and 208°C for times ranging from 30 minutes to 48 h. The hardness of solution treated samples decreased from 129 to 113 HB with increasing solution treatment temperature from 495 to 515°C. Aging increased the hardness of samples that were solution treated, and due to precipitation. Subsequent drop in hardness can be attributed to over-aging caused by coarsening of the precipitates.

Change in Brinell hardness (HB) as a function of short aging times at 190 and 208°C, of samples that had been solution treated at 495, 505 and 515°C is shown in Figure 2. These curves reveal that samples that were solid solution treated at 495 and 505°C had lower hardness after aging for short times at temperatures of 190 and 208°C. Similar results were also reported by Bray et al. [5] for Aluminum Alloy 2024 samples that had been solution treated and aged at 190°C. According to these authors, the reasons for softening of Aluminum Alloy 2024 after artificial aging for short times at 190°C are still unclear. Mukhopadhyay et al. [9] attributed this softening to reversion (dissolution) of clusters of solute (Cu and Mg). Bray et al. [5] did not agree with Mukhopadhyay et al. [9], stating that in the early stages of aging, the clusters did not go into solution, but increased in quantity. According to Bray et al. [5], vacancies retained upon quenching following solid solution treatment were annihilated within the dislocation rings during the initial stage of artificial aging. No softening was observed in Aluminum Alloy 2024 annealed at 515°C and aged for short times at 190 and 208°C. In this case, two possibilities could be considered, softening did not occur or it occurred after shorter aging times than those carried out in this investigation.

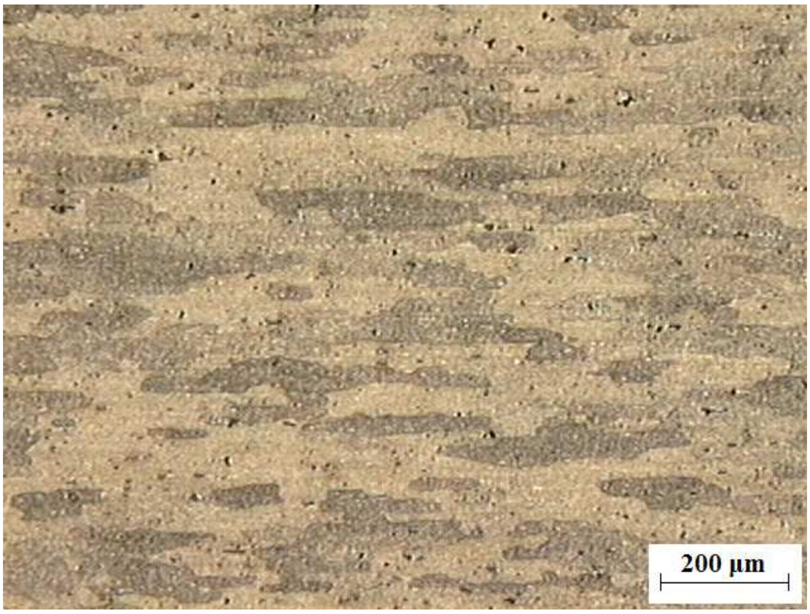


Figure 1: Typical micrograph of 2024 aluminum alloy solid solution treated for 1 h and quenched in water.

Table 2: Brinell hardness (HB) of Aluminum Alloy 2024 solid solution treated at 495, 505, 515°C for 1 hour and aged (A) at 190 and 208 C for 30 min - 48 h.

Aging Time [h]	Brinell Hardness [HB]					
	SST 495°C/1h A 190°C	SST 495°C/1h A 208°C	SST 505°C/1h A 190°C	SST 505°C/1h A 208°C	SST 515°C/1h A 190°C	SST 515°C/1h A 208°C
0	129.5	129.5	125	125	116.8	116.8
0.5	121	123.5	122.7	121	118.3	123.6
1	121	124.1	125	133.3	118.3	125.1
2	125	128.5	125	147.7	121	137.7
3	125	127.2	125	135	121	128.3
4	135	134.8	135	125	130	120.9
6	142	124.4	138.3	122.3	136.7	115.7
8	136.7	115.3	136.7	125	135	115.1
12	138.3	114	140	121	136.7	113.9
16	125	122.9	135	121	130	113.9
18	125	117.2	126.7	121	125	113.9
24	121	117.9	125.3	121	121	111.3
48	121	110.7	121	121	113	104.5

Tensile tests were conducted on samples, based on the hardness results. In general, tensile tests were carried out on samples that were solid solution treated at 495, 505 and 515°C, and aged to attain maximum hardness. Table 3 shows the yield strength (σ_{ys}), ultimate tensile strength (σ_{max}), total elongation (A) and Brinell hardness (HB) of 2024 aluminum alloy samples given the different heat treatments. The values in table 3 were averaged from three tests. Overall, aging of Aluminum Alloy 2024 increased its strength. The increase in mechanical strength (yield and tensile) is due to aging induced decrease in ductility (elongation) of Aluminum Alloy 2024. The extent of decrease in ductility does not correlate quantitatively with the increase in mechanical strength. Moreover, there seems to be a rough correlation between mechanical strength and hardness. Based on tensile test results, fatigue tests were carried out with samples that were solid solution treated at 505 °C and aged at 208°C for 2 h.

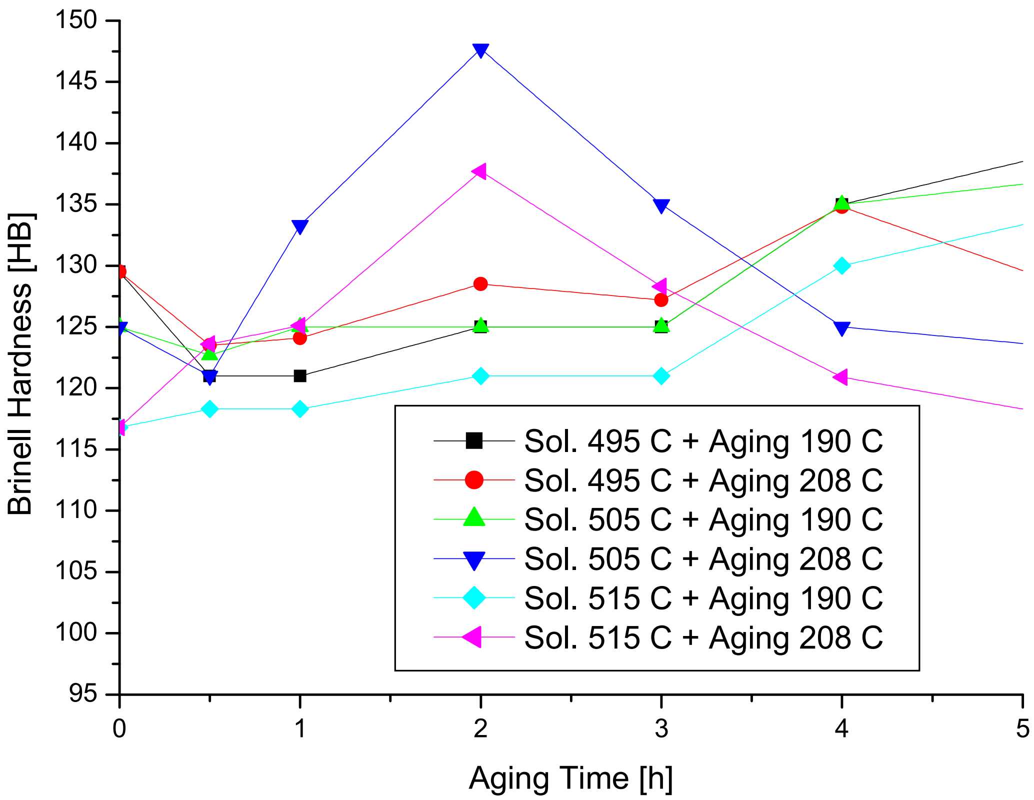


Figure 2: Brinell hardness of samples solid solution treated at 495, 505, 515°C, as a function of aging time at temperatures of 190 and 208°C

Table 3: Yield strength (σ_{ys}), ultimate strength (σ_{max}), elongation (A) and Brinell hardness (HB) of heat treated Aluminum Alloy 2024.

Heat Treatment	σ_{ys} [MPa]	σ_{max}.[MPa]	A [%]	HB
SST at 495°C/1h	306.7	468.3	20.8	129.5
SST at 505°C/1h	310	478	21.3	125
SST at 515°C/1h	306.7	475	21.7	116.8
SST at 495°C/1h and A at 190°C/6h	390	485	13.3	142
SST at 495°C/1h and A at 208°C/4h	373.3	448.3	8.4	134.8
SST at 505°C/1h and A at 190°C/6h	361.7	483.4	18.1	138.3
SST at 505°C/1h and A at 208°C/2h	400	489	13.3	147.7
SST at 515°C/1h and A at 190°C/6h	361.7	478.7	17.6	136.7
SST at 515°C/1h and A at 208°C/2h	386.7	490.3	12.9	137.7

Figure 3 shows the stress versus number of cycles to failure curve (S-N) obtained from fatigue tests on Aluminum Alloy 2024 samples solid solution treated at 505ºC/1h and aged at 208°C/2h. Of interest in this figure is that at 110.23 MPa, the samples failed after 7.8×10^6 cycles. Figures 4-6 show the fracture surfaces of samples that were fatigue tested. Figure 4 shows a typical fracture surface of a sample that was high stress/low cycle fatigue tested. Figure 4A shows the crack nucleation region. This is an important indicator of failure originating at the surface. Figure 4B shows the fracture surface of the central region of the sample. This fracture surface shows a highly dimpled structure, characteristic of ductile failure. In fracture of high strength Al-alloys, intergranular damage is induced by growth of micro-voids around coarsened precipitates. Most of the precipitates seen in Figure 4B are $CuMgAl_2$.

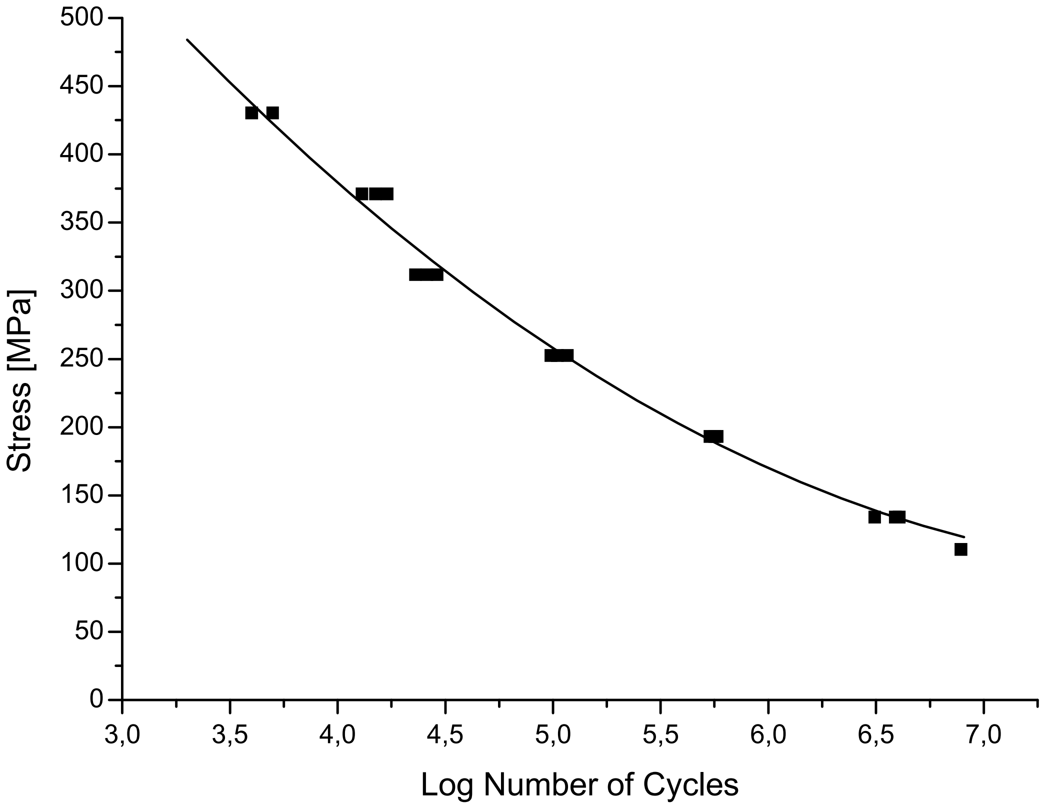
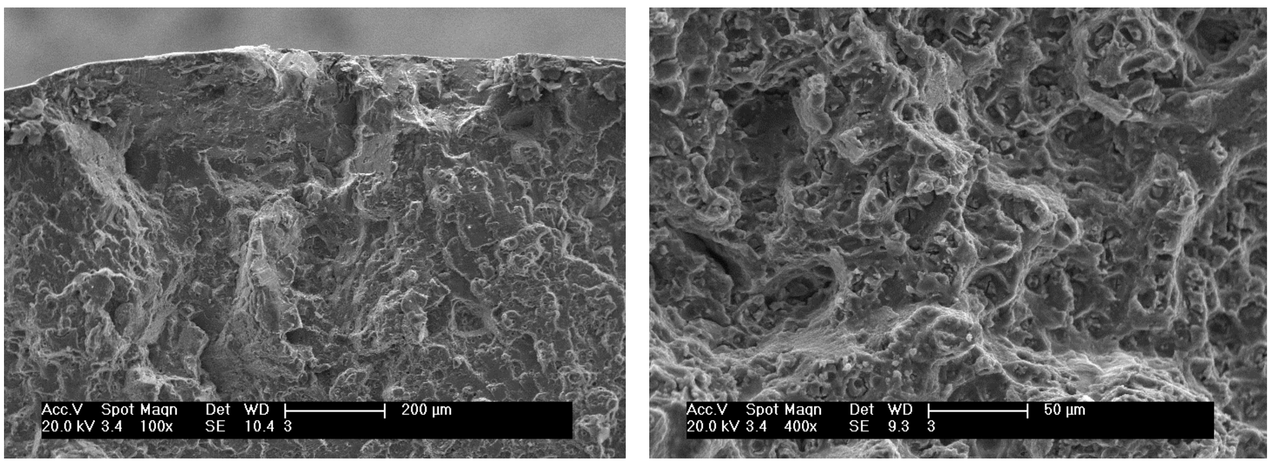


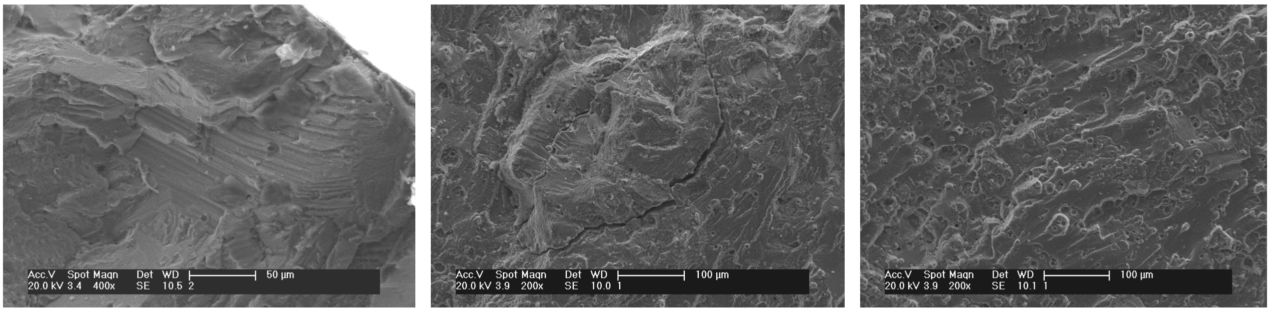
Figure 3: S-N curve obtained from fatigue tests of samples of Aluminum Alloy 2024 solid solution treated at 505ºC/1h and aged at 208°C/2h.



(A) (B)

Figure 4: Fracture surfaces of high stress/low cycle fatigue tested samples.

Figure 5 shows typical fracture surfaces of samples fatigue tested under low stress/high cycle conditions. Under these conditions the failure mechanism changed to mixed-mode. SEM observations showed that there were two different possibilities for fatigue crack nucleation. Figure 5A is a high magnification micrograph of a typical nucleation site on the peripheral region. This figure shows a cleavage facet which was caused by crystallographic crack initiation at the surface. Some multiple cracks can be also seen on the fracture surface shown in Figure 5B. Figure 5C shows the central region of the fracture surface of the sample that was high cycle fatigued. During crack propagation, pores may have intersected, as seen on the fracture surface. These pores are related to precipitates pulled out.



(A) (B) (C)

Figure 5: Fracture surfaces of low stress/high cycle fatigue tested specimens.

Conclusions

Optical micrographs revealed elongated grains, caused by rolling. Tensile tests and hardness measurements revealed that the mechanical properties of Aluminum Alloy 2024 solid solution treated at the different temperatures 495, 505 and 515°C were similar. Aging at 190 and 208°C for short periods caused a slight decrease in hardness of samples solid solution treated at 495 and 505°C. Aging increased the strength of Aluminum Alloy 2024 and decreased its ductility. The best results from the mechanical tests were observed in the case of Aluminum Alloy 2024 solid solution treated at 505°C and aged at 208°C for 2 h. At stress levels of 110.23 MPa, these samples fractured after 7.8×10^6 cycles. The fracture surfaces of samples that were low cycle fatigue tested showed mainly, precipitates and micro voids, while fracture surfaces of samples that were high cycle fatigue tested revealed crack initiation at the sample surface. The fracture surface of the high cycle fatigue tested samples revealed features that could be related to removal of precipitates from the matrix.

Acknowledgments

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