Effect of Temperature and Aging Time on 2024 Aluminum Behavior

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ABSTRACT

This study is a follow-up of previous work by the authors on the effects of processing variables on the deformation and fracture of 2024-T4 aluminum. In the previous work, four variables were incorporated into a Design of Experiments methodology: solution temperature, solution time, cooling rate and natural aging time. Solution time and cooling rate were found to be the most significant factors on the mechanical properties and microstructure of the alloy. In the current work, these variables are held constant to ascertain the relative effects of the solution temperature and aging time on material properties. Unlike the previous study, neither solution temperature nor aging time clearly dominate the measured effects. Comparisons of the current results with the previous study as well as work on 6061-T6 aluminum are made. Integration of the results of the present work into a general study of the ductile fracture behavior of aluminum alloys, involving both experimental and numerical techniques, is outlined.

INTRODUCTION

The development of the concepts of fracture mechanics throughout the 20th century allowed continuous improvement in the design of safe, efficient engineering structures [1]. Since fracture behavior can depend strongly on the processing history of the material, understanding this relationship is extremely important. For example, carbon steels quenched from high temperatures will become strong but extremely brittle, exhibiting flat fracture faces with little evidence of plastic deformation. If the quenched steels are reheated for a time (tempered), some strength is lost but a large amount of toughness is recovered, evidenced by rough fracture faces indicating the coalescence of voids following extensive plastic deformation [2]. The current work examines similar changes in the fracture behavior of 2024-T4 aluminum as the processing conditions are varied.

Above about 490°C, 2024 aluminum becomes a solid solution which is frozen in place by a subsequent quench to room temperature. The structure of the material changes over time even if it is left at room temperature (natural aging). Heating to an intermediate temperature (~190°C) can result in the formation of precipitates. The evolution of the microstructure tends to lead to an increase in both strength and fracture toughness of the alloy. Beyond an optimal aging time for a given temperature, properties decrease rapidly (overaging) [3]. A T4 designation indicates natural aging to a 'substantially stable' condition – properties of 2024-T4 aluminum tend to be stable after about 4 days of natural aging [4].

Heating to a solid solution, quenching and aging can occur in the context of processing bulk alloys but can also occur near welds. Understanding the relationship between processing history and material properties is especially important in the regions of joints as severe degradation of mechanical properties can occur. Each region of the weld (weld nugget, HAZ, etc.) may behave differently following the application of the heating/melting/cooling cycle. If tested independently, each will typically exhibit some variation of ductile fracture behavior as evidenced by the nucleation, growth and coalescence of voids. Zhang et al. [5] have successfully modeled ductile fracture by combining the work of Gurson [6], Tvergaard [7], and Thomason [8] into a 'complete Gurson model'. They have used the WELDSIM program to link the processing of welds to the resulting fracture properties of the joints. Zhang et al. [9] and Myhr et al. [10] have also worked to link the evolution of strength and hardness in aluminum alloys to changes in second phase particles during processing using principles of thermodynamics. Despite the progress that has been made, additional information about the relationships between fracture behavior of aluminum alloys and their processing history is required.

EXPERIMENTAL METHOD

Tensile dogbone specimens were machined from 2024-T4 plate stock (0.1875 in. thickness) following the dimensions set forth in ASTM Standard E8 [11]. Previous work by the authors investigated the influence of the soak (solution) temperature, soak time, quench rate and natural aging time [12]. Using a design of experiments approach, soak time and quench rate were found to have the most statistically significant effects on properties like yield strength, fracture strain and hardening behavior. Based on these results, the current work kept soak time (35 minutes) and quench rate (water quench) constant to study the effect of soak temperature and natural aging time on the evolution of the material properties. Table 1 lists the ranges of each of the variables that were studied. A central composite experimental design was used with random ordering of the tests to reduce any effects of bias [13]. This required 13 tests, 5 with identical values of the test variables (X1 = 0, X2 = 0).

Factor	Description	Star Point (-1.41)	Low (-1)	Middle (0)	High (+1)	Star Point (+1.41)
X1	Solutionising Temperature (°C)	488	490	493	496	498
X2	Aging Time (days)	1	2	3	4	5

Table 1: Values of processing variables in experimental testing

Each tensile specimen was then loaded in a screw-driven universal testing machine (Shimadzu AG-IS 50kN) while stress and strain were recorded via computer. The strain was measured using an attached extensometer. Additional displacement data was recorded using a non-contact digital image correlation system (Correlated Solutions). Figure 1 is a plot of the tensile data for the five repeated runs to illustrate the repeatability of the data. The fracture strain was approximately 18.5% ± 1.5% and the ultimate stress was approximately 500 psi ± 25 psi.

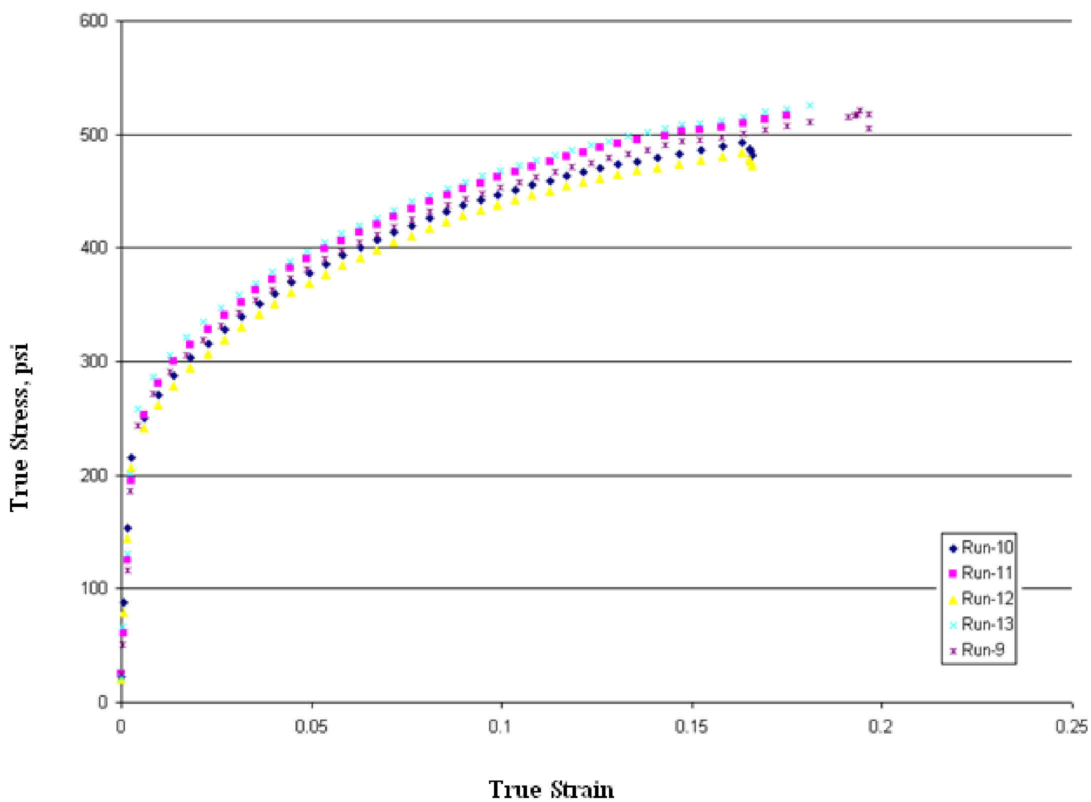

Figure 1: Repeatability of tensile data (all runs with X1 = 0, X2 = 0)

Following each tensile test, a true stress-strain curve was plotted for the data. Mechanical properties such as yield stress, maximum true stress and fracture strain were calculated. Beyond the 0.2% offset yield point, values of the Holloman hardening parameters were calculated from [14]

$$\bar{\sigma} = \sigma_Y + K\bar{\varepsilon}^n \tag{1}$$

where $\bar{\sigma}$ is the equivalent stress, $\bar{\varepsilon}$ is the equivalent plastic strain, σ_Y is the yield stress, and K and n are material constants.

STATISTICAL ANALYSIS RESULTS

After the complete experimental protocol was finished, the statistical analysis capabilities of Microsoft Excel were used to determine which, if either, of the two processing variables had a statistically significant effect on a variety of mechanical and morphological attributes of the material. The 95% confidence limit was used as the threshold for determining significance. Table 2 lists the processing factors that were found to be significant for each of the attributes.

Response	σ_Y	$\sigma_{T, max}$	ε_F	Average Particle Dia	K	n	Particle Area Fraction
Significant Factors	X1, X2	NA	$X2^2$	X2	X1	X2, X1*X2	X2, $X2^2$

Table 2: Statistically significant factors for attributes of processed 2024 specimens

Based on the statistical analysis, expressions can be created to predict the value of a given attribute based on the values of the experimental parameters. For example, Equation 2 shows the predicted statistical relationship between X1, X2 and the 0.2% offset yield strength:

$$\sigma_Y = 253.6 + 7.92 \times X_1 - 7.87 \times X_2 \tag{2}$$

It is important to understand how well these statistical relationships match the actual experimental data. Table 3 compares the average error between the statistical results and the experimental data. The error was calculated using Equation 3:

$$Error = \frac{|Actual - Estimate|}{Actual} \times 100 \tag{3}$$

Material Property	Average Error (%)	Maximum Error (%)
σ_y (MPa)	2.01	6.17
A (MPa)	0.86	1.98
σ_{UTS} (MPa)	1.86	4
$\varepsilon_{fracture}$	6.52	13.7
Area fraction (%)	4.66	14.33
Average Particle Diameter (µm)	6.79	18.77

Table 3: Comparison of error between statistical predictions and experimentally measured quantities

DISCUSSION

Natural aging time (X2) had a statistically significant effect on all of the attributes measured experimentally with the exception of the maximum true stress (no significant variables) and the strain hardening coefficient, K (X1 significant). Interestingly, a statistical effect was noted on both the average particle diameter and the particle area fraction. Previous results have indicated that natural aging should not have a strong effect on the second phase particles as microstructural changes should be limited to the establishment of zones in the crystal structure [3].

Most changes in the material attributes were relatively minor compared to the effects caused by changes in the quenching rate seen in [12]. For example, the yield strength tended to decrease with decreasing solid solution temperature and with increasing aging time. The total change however, was about 8%. The strain hardening coefficient had an even more limited response, increasing less than 1% over the range of solid solution temperatures investigated. Average area fraction of second phase particles changed from about 5.5% to about 8.5% with the average particle diameter increasing from about 2.7 microns to about 3.2 microns with increasing aging time.

Since only natural aging was used in this work, it is unlikely that any precipitates beyond Guinier-Preston zones of the first kind (GP1 zones) formed during aging [18]. However, as GP1 zones are typically very small (on the order of nanometers), it is unlikely that they could account for the changes observed in precipitate diameter at the level of microns. Additional microstructural data, particularly immediately after quenching of the samples from the solid solution temperature, is needed to verify the observed results. SEM/EDS analysis would be especially useful in characterizing the composition of the observed particles.

CONCLUSIONS

Experimental results show that natural aging time tends to have a stronger effect on material attributes than solid solution temperature when quenching rate and soak time are held constant. However, the effect of natural aging and the solid solution temperature on material properties like yield strength, fracture strain, etc., is relatively small compared to the changes seen by varying rate of quench from a solid solution. Some variation in the size and area fraction of second phase particles was noted during natural aging, in contrast to previous observations that precipitation hardening (formation of GP2 zones, etc.) occurs only during artificial aging conditions. It is unknown if this was due to contamination of the sample surface during polishing, agglomeration of non-metallic inclusions or an actual change in Al-Cu precipitates. Additional characterization of the particle chemistry is required.

These results, along with previous experimental studies on the deformation and fracture behavior of 2024 and 6061 aluminum [12,16], can be used to develop more accurate numerical models of the effects of processing history on the behavior of aluminum alloys.

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