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THE EXPERIMENTAL INVESTIGATION OF ANNEALING PARAMETERS EFFECTS ON AL2024-T3 MATERIALS' FORMABILITY AND MECHANICAL PROPERTIES

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In this study, the effects of annealing parameters on the formability and mechanical properties of Al2024-T3 sheet material were investigated experimentally. Annealing process were applied at 100 °C, 200 °C, 300 °C, 400 °C annealing temperatures and at 6 minutes, 30 minutes, 60 minutes annealing times. The forming operations were applied in 10 mm / sec deformation velocity and in V bending dies with an angle of 30 °, 60 °, 90 °, 120 °. In the experimental studies, it was determined that there was no significant change in the hardness values of the specimens at temperatures less than 300 ° C annealing temperature and 6 minutes annealing time parameters, but an irregular changes were observed in the mechanical properties of specimens. However, it was observed that there were a significant decrease in the hardness values and mechanical properties of the test specimens after the annealing temperature of 300 ° C and the annealing time of 6 minutes. It has been observed that the samples only has been formed successfully in a 30 ° die angle and at low temperatures (RT - 100 ° C - 200 ° C). It has been observed that a successful forming process has been performed in 30 ° and 60 ° die angles by increasing the annealing parameters values (400 ° C - 30 min or 400 ° C - 60 min). However, forming defects such as cracks and fractures were encountered in forming processes using 90 ° and 120 ° die angled.

Key words*: Al2024-T3, Annealing, Formability, Mechanical Properties*

1. Introduction

Aluminium 2xxx alloys are widely used in defence industry, aviation industry, and automotive industry due to their high hardness, strength, and lightweight. Al 2024-T3 alloys are most known, have low ductility and formability at room temperature due to its high mechanical properties. Therefore, it may be reqired to heat during or before the forming process in order to form the geometry and dimensions desired. In literature studies, annealing processes applied to aluminum alloys; it was often seen that solution heat treatment is applied primarily and then natural or artificial aging processes are applied. Also, it has been observed that there are studies in the literature in which all the parts are formed by laser or induction applications or only the forming area is heated. Moreover, it has been intended to

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further enhancement of the formability by different applications such as heating the female and male portions of the die set [2-9]. Khan et al. [2] investigated the effect of forming process parameters on the formability of Al 2024 alloy by experimental and finite element tests, and they reported that the formability increased by about 10%. Ortiz et al. [3] exposed different aluminum alloys to plastic deformation including Al 2024 which were tempered at various temperatures (T-O, T-8, T-62). After the deformation processes applied, they examined various properties of materials such as tensile strength, ductility, conductivity, hardness, and grain size. They suggested using tempered alloys which give low strength and high ductility values as a result of their study. Moy et al. [4] studied the effects of annealing parameters of the formability and mechanical properties of Al 2024-T3 alloy experimentally. They applied aging process at different times such as 2.5 hours, 2 days, 1 week to the samples which were solution heat-treated at 525 ℃. A significant decrease in mechanical properties and an increase, 4 - 6%, in total elongation were observed for two-days-aged samples. In addition, it was observed that the formability of the material was positively affected by the aging process. The effects of annealing process, which consist of a solution heat treatment and aging processes on the mechanical properties of Al 2024-T3 material to have been investigated in many studies. Fujda et al. [5] investigated the changes caused by the solution temperature on the mechanical properties and microstructural properties of Al2024 in annealing processes experimentally. In this study, the test samples were taken into a solution at variable temperatures between 500 - 570 ° C and were kept under vacuum for 2.5 hours. Then, the natural aging process was applied for 300 hours with water quenching. As a result of these studies, it was observed that the mechanical properties and hardness of the alloy decreased but the formability increased while process. Reis et al. [6] investigated the change in mechanical properties of heat-treated Al 2024 aluminum alloy in their experimental study. The samples were solution heat-treated at 495 ℃, 505 ℃, and 515 ℃ and then quenched. After, the samples were artificially aged at 190 ° C and 208 ° C and tensile tests were applied to the test samples for determining the mechanical properties. It was observed that the materials which were soluted at 515 ℃ and artificially aged at 208 ℃ for 2 hours had the highest yield and tensile strength. Merklein et al. [7] investigated the rearrangement of aluminum alloy properties by regional laser heating. In their work, they applied a short-term heat treatment with the Nd: YANG laser at a temperature of 400 ° C and holding times less than 5 seconds. As a result of the heat treatment, they observed a significant increase in the formability limits of the materials. Mohammadi et al. [8] investigated the bending properties of the locally laser-treated Al 2024-T3 alloy. In this study, the formability with V bending was investigated, and the bending regions of the samples were locally heated with Nd: YANG laser. Therefore, the stresses in the bending regions are reduced by local softening. As a result of the study, it was observed that the amount of spring-back after local heating decreased by 43% in the bending regions where the highest stress occurred. Chen et al. [9] studied the effects of synchronous cooling hot forming process on Al 2024 alloy microstructure and mechanical properties. They have found that the applied synchronous cooling hot forming process highly reduces residual stresses leading to spring-back and increases the dimensional stability of the final product significantly. In spite of all of these studies, heat treatment applications carried to improve the formability of Al2024 alloys can be difficult to apply because of the fact that they are expensive and require numerous consecutive metallurgical processes. In addition, the initial installation costs of such systems are very high and the high energy consumption is experienced during the implementation of some processes.

In this study, it is aimed to investigate the change of mechanical properties and formability of material experimentally by applying annealing process at different holding time and temperature parameters to Al 2024-T3 alloy. In addition, the data obtained are intended to provide guidance for industrial applications.

2. Material and Method

2.1. Material

In this study, the test samples which were used to examine the change of mechanical properties and formability were prepared using cutting guillotine shear from 2,5 mm thick Al2024-T3 sheet plate in the rolling direction. Tensile test specimens to be used for the determination of mechanical properties were also prepared by using a wire EDM machine from the Al 2024-T3 sheet plate in accordance with the ASTM-E8M standard in the rolling direction. The image of the prepared tensile test specimen given in Figure 1. Tensile test specimens used for the determination of mechanical properties were annealed together with bending test specimens. In order to analyze the chemical composition of the test materials used in the study, the chemical analysis test was performed with a spectrometer. The results obtained by the chemical analysis tests given in Table 1.

Figure 1. Al 2024-T3 Alloy Tensile Test Specimen.

Table 1. Al 2024-T3 alloy chemical analysis results.

Element (%)	Al	Cu	Mn	Zn	Fe	Ni	Zr	Pb	Other
Al 2024-T3	94,810	4,376	0,427	0,140	0,101	0,009	0,006	0,002	0,129
Nominal	90,7-94,7	3,8-4,9	0,3-0,9	Max. 0,25	Max. 0,5	-	-	-	Max. 0,15

2.2. Annealing Process and Parameters

Annealing process was applied at four different annealing temperatures (100 ℃, 200 ℃, 300 ℃, 400 ℃) and at three different holding time (6min, 30min, 60min) into test specimens which were prepared with guillotine shears. In the literature research, it was determined that the holding time at annealing temperature was applied as 1 hour for 1 inch (25.4 mm) piece thickness [10]. Since the sheet thickness of the test specimens used in this study was 2.5 mm, the holding time at the annealing temperature was 6min calculated. In addition, 30 and 60 minutes holding times were also included in these study to investigate better the effect of holding time on formability. Figure 2 shows the heating rate parameters used in the annealing process and Figure 3 shows the environment in which the annealing process takes place.

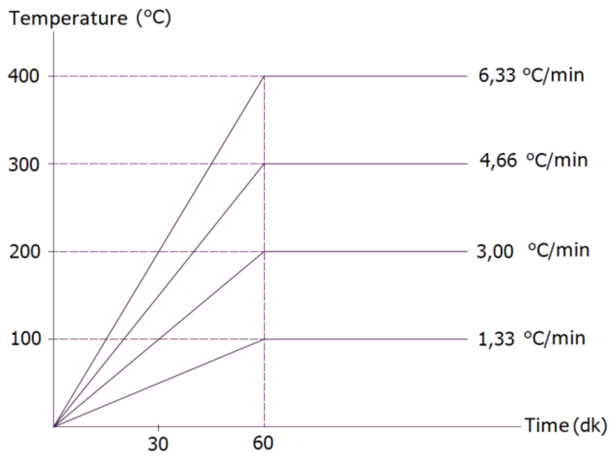

Figure 2. Heating Rate at Different Temperatures.

Figure 3. Annealing Environment (a) PID Unit Furnace; (b) Experimental Specimens.

2.3. Experimental Setup and Experimental Parameters

Figure 4 and Figure 5 shows the computer-controlled test setup in which the forming of annealed test specimens is performed. The specimens were bent at a constant deformation velocity of 10 mm/sec using with a 30° - 60° - 90° - 120° angled V bending dies and a 0 mm punch radius. Figure 6 shows the die-punch sets used in forming operations. The changes of time-dependent force in each bending occurring process were observed simultaneously with the help of data from the load cells on the device. In order to increase the reliability of the data, each experiment performed in this study was repeated 2 times.

Figure 4. Experimental Environment and Forming Device

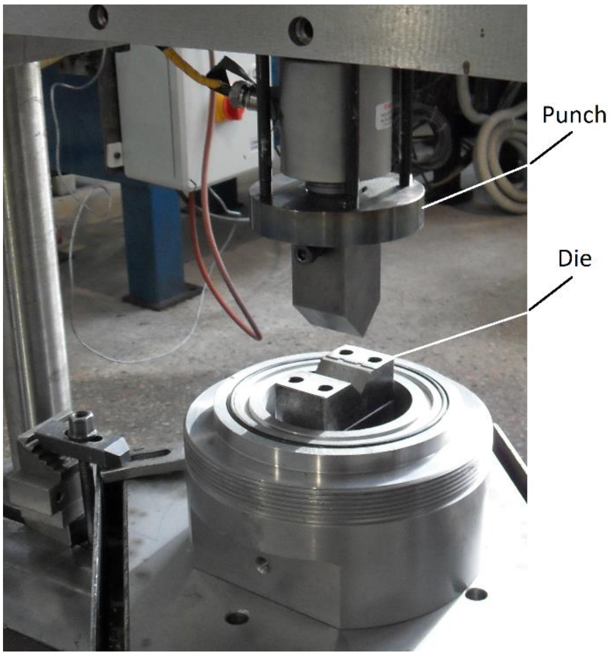

Figure 5. Detail View of Die - Punch Set.

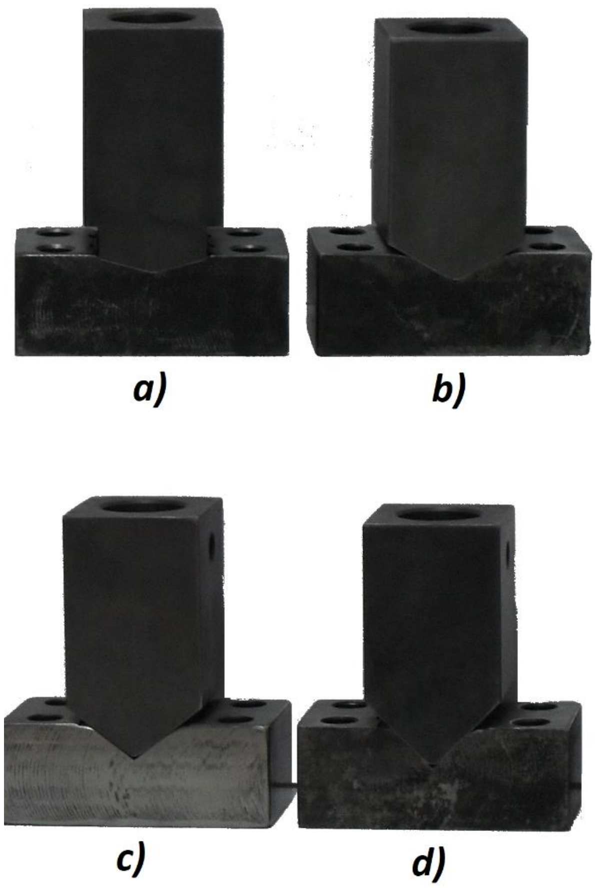

Figure 6. Forming Dies and Punches; a) 30°, b) 60°, c) 90°, d) 120°.

3. Experimental Results and Discussion

Al2024-T3 sheet material was subjected to heat treatment at different annealing temperatures at 100 ° C - 200 ° C - 300 ° C - 400 ° C for 6, 30 and 60 minutes by using electronic PID controlled annealing furnace. The changes in the mechanical properties of the annealed Al2024-T3 test specimens and their forming in various angled V bending dies (30°, 60°, 90°, 120°) were investigated experimentally. The changes in mechanical properties after annealing of test specimens were determined by tensile and hardness tests. The distribution of the values determined by the tensile tests according to the annealing parameters given in Table 2. It was observed that the annealing parameters in which applied at 100 ° C and 200 ° C temperature values were caused an irregular change in the mechanical properties of Al2024-T3 sheet metal material and did not cause a significant change in the hardness values. However, in the annealing process at annealing temperatures 300 ° C and higher, it was determined that the annealing temperature and holding time variations caused significant decreases in yield strength and tensile strength of the test specimens. In order to examine the effects of annealing parameters on the formability properties of Al 2024-T3 sheet material, V bending dies which have different bending angles at 30°, 60°, 90°, 120°, punches with zero radii, and constant deformation velocity parameters in 10 mm/s were used. It has been observed that the specimens which were annealed at 400 ℃ - 30 min and 400 ℃ - 60 min parameters can be formed in the 30 ° and 60 ° angled V bending dies without any forming defects such as cracking or breaking. Specimens that were annealed at RT - 100 ° C - 200 ° C can be formed without any forming defects in a 30° angled die set. In Table 3, the obtained data shows as a consequence of bending operations. In addition, the results of the hardness test which were performed in three repetitions at 10 mm gaps, shown in Figure 7.

Table 2. Tensile Test Results for Al 2024-T3 Annealing Parameters.

Annealing Heat (°C)	Holding Time (min.)	σ_y (MPa)	UTS (Mpa)
RT	-	350,112	474,497
100	6	363,259	480,392
	30	355,548	473,828
	60	361,687	479,419
200	6	348,695	463,418
	30	382,157	482,950
	60	381,225	480,102
300	6	348,395	436,760
	30	309,856	403,878
	60	291,348	384,724
400	6	198,621	311,857
	30	130,115	241,611
	60	100,586	237,437

Table 3. Obtained Data As A Result of Bending Operations.

Die Angle	Annealing Heat (°C)	Holding Time (min.)	Description	Die Angle	Annealing Heat (°C)	Holding Time (min.)	Description
30°	RT	-	Success	90°	RT	-	Crack
	100	6	Success		100	6	Crack
		30	Success			30	Crack
		60	Success			60	Crack
	200	6	Success		200	6	Crack
		30	Success			30	Crack
		60	Success			60	Crack
	300	6	Crack		300	6	Broken
		30	Crack			30	Broken
		60	Crack			60	Broken
	400	6	Success		400	6	Crack
		30	Success			30	Crack
		60	Success			60	Crack
60°	RT	-	Crack	120°	RT	-	Broken
	100	6	Crack		100	6	Broken
		30	Crack			30	Broken
		60	Crack			60	Broken
	200	6	Crack		200	6	Broken
		30	Crack			30	Broken
		60	Crack			60	Broken
	300	6	Crack		300	6	Broken
		30	Crack			30	Broken
		60	Crack			60	Broken
	400	6	Crack		400	6	Crack
		30	Success			30	Crack
		60	Success			60	Crack

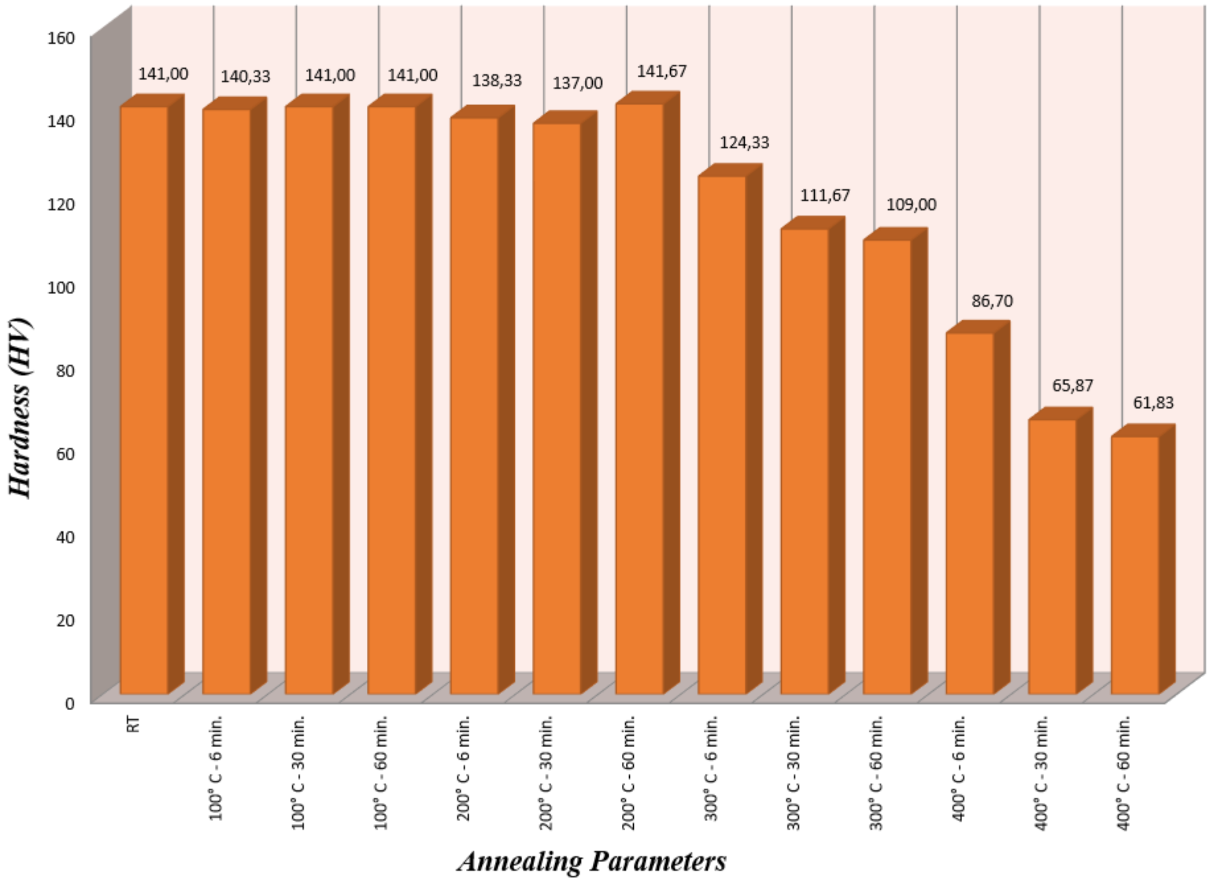

Figure 7.Variation of Hardness Values According to Annealing Parameters.

4. Experimental Results and Discussion

In this study, 2024-T3 aluminum alloy was annealed at variable annealing temperature and holding times. It has been aimed to determine the optimum annealing parameters in which no cracks and breaks occur for the ideal forming. In addition, the effects of annealing on the mechanical properties and hardness values of Al 2024-T3 sheet metal material were investigated. The results obtained from the experiments are given below.

i. An irregular change in yield strength and tensile strength of the annealed specimens starting from room temperature up to 300 °C annealing temperature was determined. However, a significant decrease in yield strength and tensile strength was observed in 300 °C - 6 min annealing parameters. At 400 ° C - 60 min annealing parameters, the heat-treated specimens initially had 350,112 MPa yield strength, decreased by 71.27% to 100,586 MPa. And at the same annealing parameters, a maximum tensile strength in which decreased by 49.96% from 474,497 MPa to 237,437 MPa.

ii. As a result of the annealing process, it was observed that the hardness values of Al 2024-T3 alloy did not change significantly until the annealing process was carried out at 300 °C. Significant decreases in hardness values were observed annealing parameters in the case of 300 ° C - 6 minutes. Also, it was measured that in the 400 ° C - 60 min annealing parameters the initial hardness of 141 HV decreased by 56.15% decreased to 61.83 HV value.

iii. At low temperatures, RT - 100 ° C - 200 ° C, annealed test specimens can be formed only in 30 ° angled bending dies without any cracks or fractures. However, when the annealing parameters were changed to 400 ° C - 30 min or 400 ° C - 60min was observed that it could be formed without any defect in 60 ° angle bending dies.

iv. It was observed that Al2024 – T3 test specimens which were heat-treated at 400 ° C - 60 min annealing parameters could not be formed in 90 ° and 120 ° angled V bending dies.

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