An Experimental Approach and Constructing a New Non-Linear Regression Model for Prediction the Anisotropy Parameters of Annealing Treated Commercially Pure Aluminum Sheets

Jabbar H. Mohmmed
Materials Engineering Department, University of Technology/Baghdad
Email: jabbaraljanaby@yahoo.com
Ali A. Mohsen
Materials Engineering Department, University of Technology/Baghdad
Bassam A. Ahmed
Electromechanical Engineering Department, University of Technology/Baghdad
Najmuldeen Yousif Mahmood
Mechanical Engineering Department, University of Technology/Baghdad

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ABSTRACT

Earing is a common phenomenon in deep drawing process that increases the waste of metal. This phenomena is affected by material anisotropy, thus, it is important to study the effects of material parameters on this material behavior. This paper focuses on identify the optimal condition of annealing treatment which result in higher value of normal anisotropy and lower value of planar anisotropy which lead to reduce the waste material in subsequent forming processes. Therefore, in this study, anisotropic behavior and formability of commercially pure aluminum thin sheets was investigated after annealing the samples at different temperatures (350, 400, and 450) °C. Uniaxial tensile tests were carried out at room temperature (25°C) to evaluate formability parameters. For this purpose different tensile test samples in the directions of 0°, 45° and 90° in respect to the rolling direction were prepared. In addition to, metallographic test was carried out to as-received and annealed samples to observe the changes in microstructure.

Plastic strain ratio and planar anisotropy of samples were calculated from the tensile test data. Based on the tensile test results of samples, the earing phenomenon due to planar anisotropy in commercially pure aluminum sheet was analyzed. The results indicate that the annealing at 400°C brought the optimum conditions.

Moreover, new regressions model for prediction the anisotropy parameters of sheet metal using statistical techniques (SPSS software) were constructed in this work. The experimental data were compared to those predicting values. A comparison clearly indicates that there are good identification between measured and predicted values with multiple correlation coefficients R of 0.932 and accuracy of about 87 %. The results reveal that the proposed model is effective and reliable tool to obtain accurate prediction of the anisotropy behavior of metal sheets.

Keywords: anisotropy phenomenon, annealing treatment, regression model, commercially pure Al.

INTRODUCTION

In recent years, cold rolled sheet aluminum have been increasingly used in various industries especially in automotive and aerospace industry in addition to production of domestic appliances because of its excellent corrosion resistance, high strength/weight ratio, and good formability [1]. However, some microstructural complexities (formation of different textures) may be developed during their rolling which have inverse impact on its properties. It was referred to the so called anisotropic effect, a phenomenon that is mainly associated with the deep drawing processes [2].

Deep drawing is one of the most important processes for sheet forming which involves conversion of flat sheets of metal into different parts with useful shape [3, 4]. This process is a

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2412-0758/University of Technology-Iraq, Baghdad, Iraq

complicated forming process and characterized by tensile/compressive stresses. It is involved tension (at cup wall), bending (at punch and die corners) and compressive stresses (at flange). High tensile strength at formed wall zone and high ductility of material at flange region are required from initial material for the successful deep drawing [4, 5]. Recently, modern industry used the deep drawing process in many applications, especially, in the automotive bodies, aircraft panels. There are several interrelated factors which affected deep drawing process include the geometry and material of sheet blank and the tools, the conditions of interface between tool and material, and the mechanics of plastic deformation [6]. Among these factors, the properties of blank material have more significant effects on the quality of formed part and in determination of process parameters [7].

Anisotropy of materials has the most important role in determination of the ability of the sheet for deep drawing. The materials which formed at high level of plastic deformation will appear anisotropy behavior in their properties due to the preferred orientation of the grains at structure [8]. Earing in drawn cups is one problem associated with varying plastic strain ratio at different directions. Earing can be a big problem, as the ears must be trimmed before further processing can be continued. This produces a lot of waste material and hence lost money.

The current research presents the effects of annealing treatment conditions on the anisotropy behavior and formability of commercially pure aluminum sheet. Moreover, a new mathematical model for prediction the anisotropy parameters of sheet metal was constructed.

Anisotropy Measurement

Anisotropy is typically characterized by Lankford's coefficient (r),frequently called the plastic anisotropy parameter or (r-value) which represents the ratio of the true strain in width direction 'w' to the true strain in thickness direction 't', is evaluated through uniaxial tensile tests [9, 10]

$$r=\frac{strain_w}{strain_t}=\frac{\epsilon_w}{\epsilon_t}=\frac{\ln w_0/w_f}{\ln t_0/t_f} \qquad \ldots 1$$

Where ϵ_w is the strain in width, and ϵ_t is the thickness strains at a uniaxial tension test.

Due to difficulty in measuring thickness changes with sufficient precision, in practice an equivalent relationship is commonly used, based on length and width strain measurements as follows [9, 10]:

$$from\ volum\ costancy\ l_0w_0t_0=l_fw_ft_f \Rightarrow \frac{t_0}{t_f}=\frac{l_fw_f}{w_0t_0}$$

$$\therefore \epsilon_t=ln\frac{l_fw_f}{l_0w_0}$$

$$r=\left(\frac{\ln w_0/w_f}{\ln l_fw_f/l_0w_0}\right) \qquad \ldots 2$$

This is normally carried out with samples produced at 0, 45 and 90 degrees from the rolling direction. Since the r-values vary for the different directions an average value can be used, which is called normal anisotropy, and is defined as [9, 10]:

$$r_n=\frac{r_0+r_{90}+2r_{45}}{4} \qquad \ldots 3$$

Where: the index indicates the angle from rolling direction.

The size of the average normal anisotropy depends not only on the type of sheet metal and its processing history, but also on the grain size, increasing as the grain size increases.

For deep drawing operations a high r-value indicates that the material can be relatively easily compressed in the flange while the wall of the drawn part can sustain high load without excessive thinning and fracturing and this indicates that the material is good for deep-drawing operations.

Another description of anisotropy is the variation of the r-value in the plane of the sheet, which is called planar anisotropy and is defined as [9, 10]:

$$\Delta r = \frac{r_0 + r_{90} - 2r_{45}}{2} \qquad \dots 4$$

For deep drawing operations this value correlates well with the ‘earing’ of a deep-drawn cylindrical cup. When Δr is zero, no earing occurs in the part. Thus, deep draw ability increases with high r values and low Δr values, i.e for a successful sheet metal forming, the normal anisotropy must be as large as possible whereas the planar anisotropy must be as small as possible.

Experimental work

Material Selection:

The cold rolled commercially pure aluminum sheet) 99.1%Al) with a thickness of 1 mm was selected as research material in this investigation.

Work Procedure:

In order to measure r-value for used materials (commercially pure aluminum), samples for tensile test for two conditions of the materials, as-received and annealed conditions in different temperatures (350, 400, 450)°C and in different directions (0°, 45°, 90°) relative to rolling direction was prepared.

Number of samples is (36), (12) samples for each direction, and the samples of each direction are divided into three groups, each group consist of (3) samples for each temperatures.

The test procedure was according to standard ASTM-E517 [10]. For more accuracy in measurement the displacements and strains components a grid was applied on samples surface. The shape and dimension of the sample are shown in Fig.1.

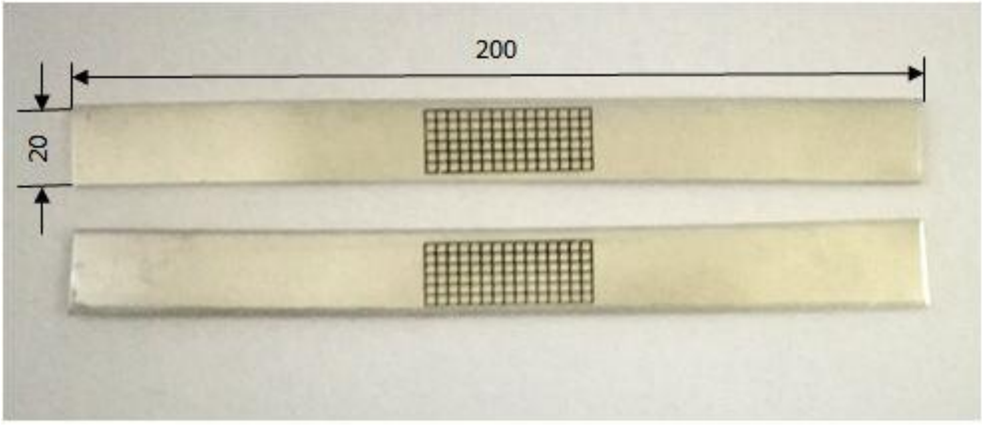

Figure. 1 Machined Rectangular Tension Test Specimens, Parallel Strip, for r Determination (all dimension in mm) [10].

According to the previous a knowledge of the original dimension of the of width (w_0), thickness (t_0) and the length (l_0) to the gauge length of (50mm) the true strains towards the width, thickness and length can be calculated to every test according to the equations:

$$\epsilon_w = ln\frac{w}{w_0} \quad ...5$$

$$\epsilon_t = ln\frac{t}{t_0} \quad ...6$$

$$\epsilon_l = ln\frac{l}{l_0} \quad ...7$$

The anisotropy coefficient (r-value), normal anisotropy (r_n), and planar anisotropy (Δr) can be determined by equations (1-4).

Microstructure test:

Metallographic samples were cut from the initial sheet in rolling direction. The as-received and annealed samples will be prepared by mounting, grinding, polishing and then etched (by etchant solution contains: 2ml HF + 3ml HCl + 5ml HNO_3 + 150ml distilled water) to analyze the microstructure, and observe the change in grain structure. Optical microscope was used to perform this test.

Mathematical model

A mathematical model using statistical techniques for the prediction of anisotropy parameters was performed for the tensile test data obtained from laboratory experimental work. The variables used in the prediction models were divided into two data sets; dependent variables (r-value) and independent variables. The definition of independent variables and their values are given in Table 1. The number of experimental data was twelve including two experimental data, which chosen randomly, as control point. These two control points don't involve in building the mathematical model but used to test the flexibility and the validity of the prediction model. While, the remaining experimental data used to build up the prediction model. All experimental data was presented in Table 2.

Table 1. Definition of independent variables used in buildup the prediction model

Designations of independent variable	Name of variable	Value
$\mathcal{X}_1$	Orientation respect to RD (°)	0.45,90
$\mathcal{X}_2$	Annealing temperature (˚C)	0,350,400,450

Table 2. Experimental data for measured and predicted values of r-value

No	Orientation respect to RD	Annealing temperature	r-value (measured value)	r-value (predicted value)
1	0.00	0.00	0.33	0.328
2	45.00	0.00	0.63	0.50
3	90.00	0.00	0.37	0.50
4	0.00	350.00	0.51	0.525
5	45.00	350.00	0.81	0.697
6	90.00	350.00	0.60	0.697
7	0.00	400.00	0.59	0.563
8*	45.00	400.00	0.85	0.735
9	90.00	400.00	0.62	0.74
10	0.00	450.00	0.55	0.563
11*	45.00	450.00	0.84	0.735
12	90.00	450.00	0.62	0.74

*** Control point**

Results and Discussion

Microstructure:

The microstructures of as-received and annealed samples, for the commercially pure aluminum sheet are shown in Fig. 2. It can be observed that after annealing treatment, the recrystallization process was taken place for the aluminum grains.

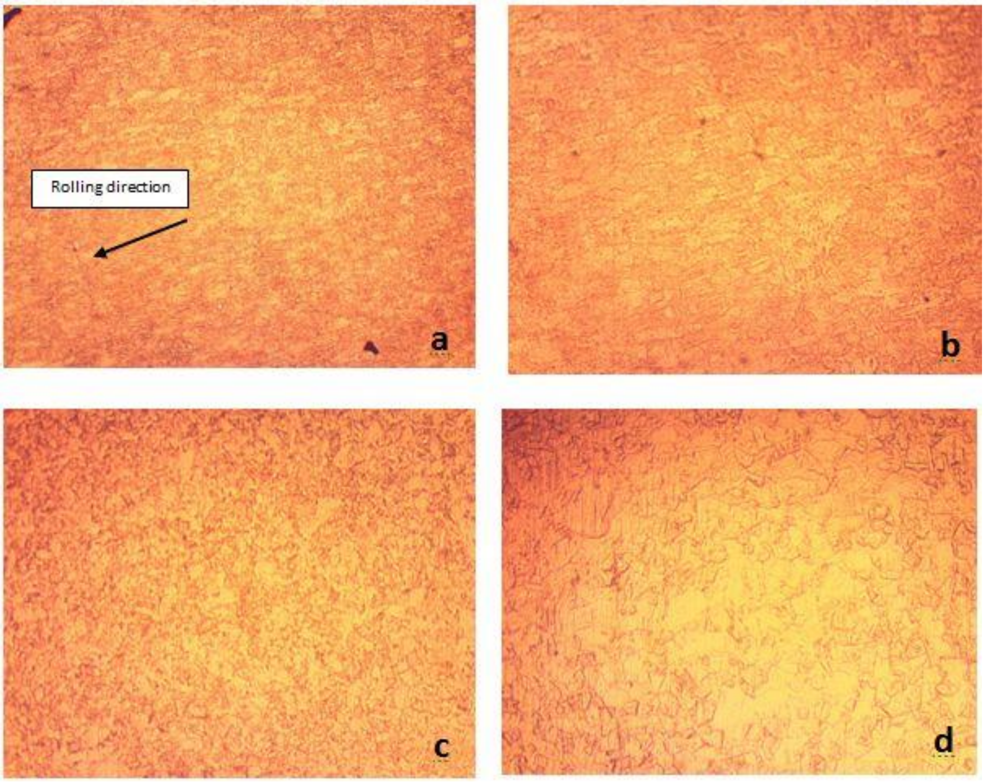

Figure 2 Microstructure (20x) of commercially pure Al for (a) as received; (b) annealed at 350°C; (c) annealed at 400°C; (d) annealed at 450°C.

Formability parameters

Tensile test was used to determine the formability parameters $(r_n, \Delta r)$ as shown in Figure 3, Figure 4, and Table 1.

For isotropic materials r -value equal to 1, and materials that have a value of r greater than 1, possess high resistance to plastic flow in sheet thickness direction. Table 1 shows r –value of all samples. The maximum r –value for as received samples was 0.63 at 45^o direction, while the minimum value was 0.33 at 0^o direction. For annealed samples, r –value display close responses in the 90^o direction as the values lie between 0.60 and 0.62. The r –value in 45^o direction was always higher than at 0◦, 90^o directions. The r –value was increased for annealed samples as compared with as received conditions in all cases, and this suggests that there is an enhancement in the formability and reduction in anisotropic properties of Al sheet.

Table 3 Formability parameters of commercially pure Al

Annealing temperature	Orientation respect to RD	r-value	r_n	Δr
As-received	0	0.33	0.49	-0.28
	45	0.63		
	90	0.37		
350	0	0.51	0.68	-0.255
	45	0.81		
	90	0.60		
400	0	0.59	0.7275	-0.245
	45	0.85		
	90	0.62		
450	0	0.55	0.7125	-0.255
	45	0.84		
	90	0.62		

For deep drawing operations a higher value of normal anisotropy (r_n) indicates that the material can be relatively easily compressed in the flange while the wall of the drawn part can sustain high load without excessive thinning and fracturing and this indicates that the material is good for deep-drawing operations [10].

Figure 3 present the variation of normal anisotropy value with the annealing temperature. It is clearly from this figure that the high value for normal anisotropy is at samples annealed at 400°C. This attributed to the reduction in the numbers of deformed grains and the formation of a new free strain and recrystallized grains (Fig. 2). This indicates that this sheet possess higher draw ability than the sheets annealed at other temperatures.

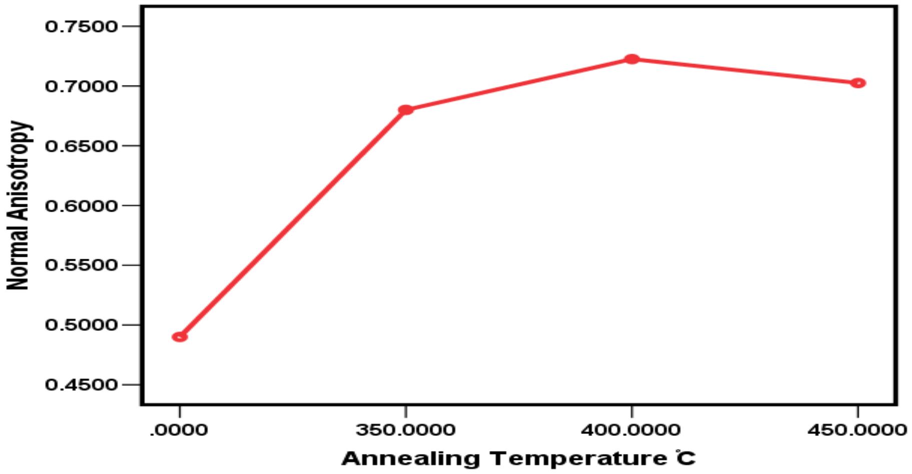

Figure 3 Effect of annealing temperatures on normal anisotropy of commercially pure Al.

Another description of anisotropy is the variation of the r-value in the plane of the sheet, which is called planar anisotropy (Δr). Planar anisotropy is directly related to earing. As the magnitude of the Δr value increases, the ear heights increase [11]. Therefore for deep drawing operations, suitable materials must have smaller planar anisotropy values in magnitude [11].

Figure 4 presents the effect of annealing temperature on planar anisotropy values. It can be noticed from this Fig that the lower values was obtained at the samples annealed at 400 which brought the minimum height of earing.

Therefore, the samples annealed at 400°C presented better formability than that of the samples annealed in other temperatures. Higher ductility was noticed at samples annealed at 450°C other samples. But, at the same time, the draw-ability of these samples was lower as compared with the samples annealed at 400°C. These may attributed to the increasing in grain refinement for samples annealed at 400°C which result in increasing in the grain boundaries area which rise the amount of energy required for the dislocations movement. Therefore, the material can withstand higher rates of plastic deformation before fracture which lies in enhancing the draw-ability. A refined and recrystallized grains of samples annealed at 400°C have better formability in all regions. Also, it can be noticed that the samples annealed at 450°C have r-value which are smaller than that of the samples annealed at 400°C in all cases. This may be explained by the fact of the r-value is related to the grain orientation at different conditions of heat treatment. Moreover, the results indicate that the samples annealed at 400°C have stretch-ability and draw-ability more than the sheets annealed at 350°C because of the presence of rolled grain microstructure (Fig 2 b).

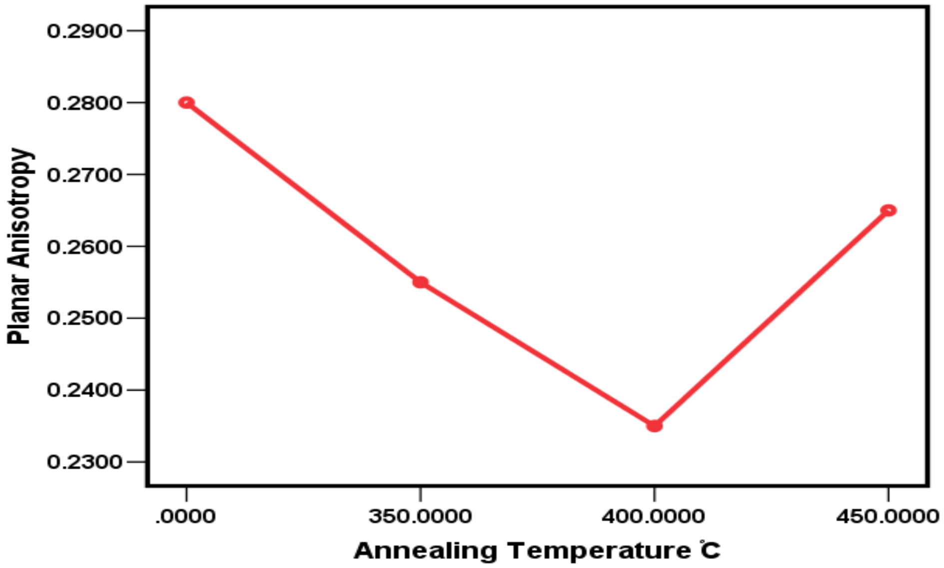

Figure 4 Effect of annealing temperatures on planar anisotropy of commercially pure Al.

Results and discussion for mathematical modeling

After processing of experimental data by using (SPSS 21 package), a mathematical model for predicting the r-value of cold work commercially pure aluminum annealed at different temperatures and in different orientation of rolling direction was obtained:

$$r = (x_1 < 45) \times 0.252 + (x_1 \geq 45) \times 0.422 + 0.816e^{-10.722(x_1-44)} + \frac{(x_2 < 400) \times 0.275}{1 + 2.501e^{-6.621x_2}} + (x_2 \geq 400) \times 0314 + 0.816e^{-8.774(x_2-399)} \quad \ldots.8$$

Where:-

r: r-value, $\mathcal{X}_1$: Orientation respect to RD (°), $\mathcal{X}_2$: Annealing temperature (˚C)

Note the $(x_1 < 45, x_1 \geq 45)$ and $(x_2 < 400, x_2 \geq 400)$ terms in the expression. These terms return a value of 1 when true and 0 when false, and are used to create the segmented model.

The new multiple nonlinear regression models yielded excellent correlation coefficients for the prediction of r-value at different annealing temperatures and orientation of rolling direction.

The value of the multiple correlation coefficients R was 0.932 which reveals the strong relationship between independent and dependent variables.

The average percentage deviation (Φ) value was 13%, this means that the regression model could predict the r-value with about 87 % accuracy of the experimental data set. This small error 13% may be due to some factors that were not taken into consideration when building a mathematical model like the sample thickness, and the rate of cold working.

Figure 5 presents the comparison between the measured (actual) values and predicted values of all experimental data for r-value.

It can be observed from Fig. 5 that there are close matches between predicted and measured values for all cases. These reveal that the new multiple nonlinear regression model is effective and reliable tool to predict the anisotropy parameters of sheet metals.

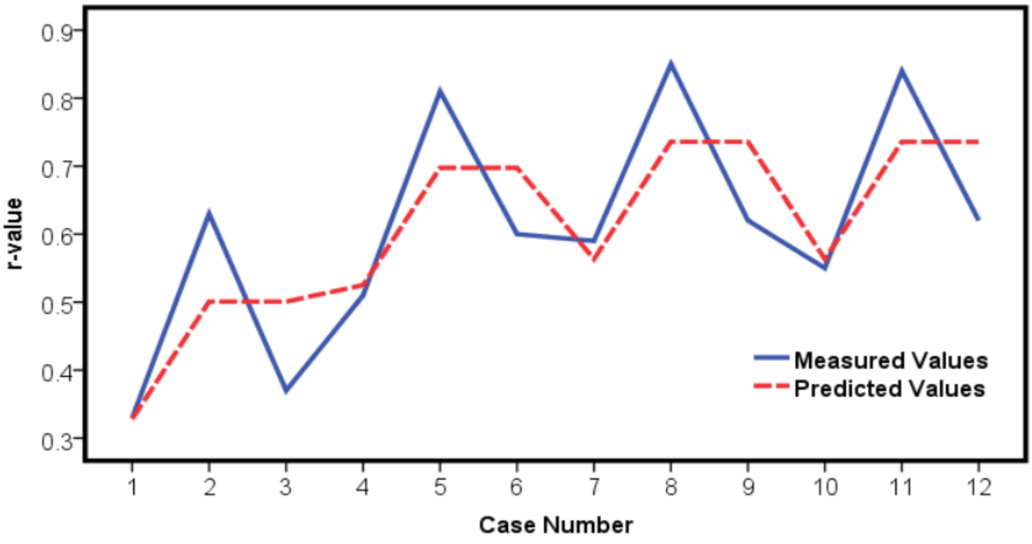

Figure 5 Comparison between Measured and Predicted values for the experimental data for r-value

CONCLUSION

Based on the results and discussions presented in the foregoing sections, the following conclusions can be drawn:

- Formability of commercially pure Al sheets could be improved by annealing operation and recrystallization process.
- The sheets annealed at 400°C possess good ductility, higher normal anisotropy r_n value, and lower Δr value that indicated the best formability as compared to sheets were annealed in other temperatures.
- The multiple non-linear regression models could predict the r-value of commercially pure aluminum with higher accuracy for different orientation of rolling direction, and annealing treatment temperatures.

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