Effect of Process Parameters on Formability of Aluminum 2024

Irfan Mahmood Khan, Umair Ismail, D. Noman, M. Zeeshan Siddiqui and M. Shahzad

***Abstract*— This paper encompasses experimental investigation regarding the forming of aluminum 2024. Effect of processing parameters on material flow, formability and hardness of the alloy was studied in detail. Conventional press with movable punch was employed for sheet forming of aluminum alloy. Forming process involved cold working of aluminum 2024 during deep drawing (forming) operation. Cold work resulted in grain elongation and hardening of the alloy. Premature fracture occurred before reaching the desired depth. Tuning the process parameters facilitated the material flow, ultimately improving the formability of the alloy with current process. FE analysis was performed using ANSYS® for predicting and augmenting forming behavior of the alloy.**

***Index Terms*— Aluminum 2024; Annealing; Strain Rate; Clamping Force; Material Flow**

I. Introduction

There is a huge class of parts, both in size and complexity that can be made from sheet metals, usually produced in large quantities by conventional forming method on mechanical presses.

There are various types of metal sheet forming processes. The primary forces are frequently tensile, with indirect compressive forces developed by the reaction of the work piece. The metal flow is therefore under the combined stress state, i.e., extrusion, wiredrawing, tube drawing.

In deep forming of aluminum alloys both thinning of sheet along the profile and premature fracture is of main concern [1, 2]. Strain hardening occurs during most working and forming operations of aluminum alloys. It is a very common technique in manufacturing and is the desired process in the fabrication of hemispherical cups and cylindrical heads [3].

Irfan Mahmood Khan is with Pakistan Space & Upper Atmosphere Research Commission (SUPARCO) Headquarters, P.O. Box No. 8402, Karachi-75270, Pakistan (Corresponding Author; phone: 92333-7627271; fax: 92-21-32594213; e-mail: irfanmkk@gmail.com).

Umair Ismail is with Pakistan Space & Upper Atmosphere Research Commission (SUPARCO) Headquarters, P.O. Box No. 8402, Karachi-75270, Pakistan (e-mail: m.umayr@yahoo.com).

Danish Noman is with Pakistan Space & Upper Atmosphere Research Commission (SUPARCO) Headquarters, P.O. Box No. 8402, Karachi-75270, Pakistan (e-mail: dnshnoman@yahoo.com).

Muhammad Z4eeshan Siddiqui is with Pakistan Space & Upper Atmosphere Research Commission (SUPARCO) Headquarters, P.O. Box No. 8402, Karachi-75270, Pakistan (e-mail: zeeshan@pnec.nust.edu.pk).

Majid Shahzad is with Pakistan Space & Upper Atmosphere Research Commission (SUPARCO) Headquarters, P.O. Box No. 8402, Karachi-75270, Pakistan (e-mail: dr_majid@engineer.com).

Forming process parameters may be altered in order to yield optimum thickness along the formed profile and depth of formed part including acceptable wrinkling. Changes in lubrication can alter the mode of material flow during forming, create or eliminate defects, alter the surface finish and dimensional precision of the product and modify product properties [4].

In the present study, the effects of process parameters in cold forming of AA 2024-TO will be studied and parameters will also be analyzed and optimized through FEA. Process parameters such as clamping force, strain rate, no. of steps, step size, intermediate annealing and lubricant application zones are improved in order to achieve finest combination of process parameters. The results achieved are in good agreement with the FEA results.

Al-2024 is an Al-Cu-Mg alloy with high strength; its tempers include T3, T8, TO, and T62 and are often used in the T3 and T4 tempers. It has a high response to artificial aging, especially if cold work is applied prior to aging (T8 temper) [5].

Precipitation hardenable alloys are usually formed in the T4 (naturally aged condition) or in the TO (annealed) condition. They are rarely formed in the peak aged (T6 or T8) conditions where both the necking and fracture limits are low [6, 7].

Immense research work is available on the forming of aluminum alloys. Hamed Ziaei Poor et al. discussed parameters to reduce wrinkling in hydroforming [7-9]; M. Zampaloni et al. performed numerical and experimental study on the stamp hydroforming of aluminum alloys, G. Centeno et al. determined the formability limits through the evaluation of necking and fracture in both stretch forming and single point incremental forming [10]. The previously available research scarcely covers the detailed optimization of process parameters in conventional forming methods to achieve forming of hemispherical cups.

In the current research, the effect of process parameters on forming characteristics of aluminum 2024 in TO temper will be investigated and parameters will be optimized through finite element analysis [11-13]. Multiple process parameters such as clamping force, strain rate, number of steps, step size, lubricant application and intermediate annealing are optimized in order to attain suitable combinations of process parameters. The experimental results attained were congruent with FE analysis results. Moreover, the impact of process parameters on the material's microstructure has also been studied.

II. Procedure for Sheet Metal Forming

A. Press Characteristics

Conventional Press was employed for forming of Aluminum 2024 sheets. Strain rate and speed of the punch were uncontrolled. Characteristics of press are as follow:

TABLE I
CHARACTERISTICS OF CONVENTIONAL PRESS

Sr. NO.	Press Parameter	Value (mm)
1	Punch diameter	376.6
2	Die diameter	383.3
3	Clearance	3.35
4	Die Radius	15
5	Stroke Size	5-30

B. Standard Operating Procedure

Mechanical properties of Aluminum 2024 and standard operating procedure for metal sheet forming is illustrated in impending text.

TABLE II
STRENGTH OF ALUMINUM 2024 [9]

Temper	UTS (MPa)	Y.S (MPa)
TO	186-220	76-96
T62	450-480	380-400

Table III
HARDNESS AND PERCENTAGE ELONGATION OF ALUMINUM 2024 [14]

Temper	Hardness (HV)	% Elongation
TO	50-59	20-22
T62	132-135	9-12

Lubrication (Molykote) is applied on punch and both surfaces of the stock for improving material flow. The stock is placed over the die in stock holder (Dimensions: 448 x 448 mm). Clamping plate is fixed above the stock to avoid the upward displacement of the stock. Set of 12 layers of pads is placed around the die for damping of punch speed; each layer is removed after every 30 mm depth. Punch is dropped on the stock which presses the stock up to the depth step size which can be varied from 5 mm to 30 mm.

C. Forming of Aluminum 2024-TO

Annealing of three sheets (Dimensions: 400 x 400 x 2.7) was carried out followed by furnace cooling to transform it into T-O temper. Forming of annealed sheets was performed by 10 mm strokes till 50 mm depth followed by 5 mm steps till 70 mm depth. Visible wrinkling and bulging was observed in the formed specimen. The stock underwent displacement as its size was shorter than the standard stock size for this particular die. The process was stopped and stock was dismounted after witnessing the wrinkling effect.

Three sheets with standard stock size (Dimensions: 448 x 448 x 2.7 mm) were prepared and annealed to cater the wrinkling issue. Forming of sheets was carried out according to the practiced operating procedure, i.e. step size of 10 mm up to 50 mm depth followed by 5 mm steps till final depth. These sheets were formed till 70 mm depth on the scale but the actual depth was 85 mm at fracture, i.e. scale error of 15 mm was observed.

Three more standard sized sheets were annealed and formed till 80 mm actual depth. Sheets were then intermediate annealed at 430 for 2 hours followed by furnace cool and formed again. The final depth upon fracture was 93 mm. Annealing increased formability but its effect was not substantial because of permanent deformation which had already taken place prior to annealing, i.e. grain elongation and pinning of dislocations.

Thinning of the sheet at center of the dome was observed after forming process. It was observed that the pads used for damping of punch speed exerted excessive force on the edges of the sheet resulting in augmented clamping. Extreme clamping force on the sheet restricted the material flow from edges to the center. This issue was rectified by using spacers between the stock and stage.

The use of spacers proved expedient for facilitation of material flow from edges to the center. Three standard sized annealed samples were formed using spacers around the periphery. The formed depth increased from 85 mm to 107 mm by incorporation of spacers. It was observed that Molykote aggravated material flow and reduced friction between mating surfaces. The thickness of the stock reduced drastically at the center as maximum force was exerted by the punch at the center of the stock. It was required to control the thickness reduction in the sheet.

For the next three specimens, Molykote was only applied on the edges of sheet to allow maximum flow from edges and minimum from the center. Formed depth of 140 mm was achieved by using spacers along with modification in Molykote application. The specimen was formed till fracture to estimate its maximum forming limit. Formed depth of 150 mm was achieved without significant decrease in thickness of the stock prior to fracture. Total formed depth after fracture was 162 mm.

Fig. 1. Images of formed (fractured/non-fractured) hemispheres

The effect of intermediate annealing on the formability of the specimen by incorporating spacers and Molykote modification was studied by forming three specimens till 70 mm depth followed by intermediate annealing. The final depth prior to fracture was 170 mm. The depth after fracture was 180 mm.

It is evident from the above process modifications that the formability of the alloy can be improved significantly by using spacers, intermediate annealing and application of Molykote on edges only.

TABLE IV
LIST OF MATERIALS USED IN THE RESEARCH [4]

Sr. No.	Material	Heat Treatment
1	2024-TO (A)	Solution heat treated at 420 0C for 2 hours followed by slow furnace cool [15].
2	2024-TO (B)	Same as above
3	2024-TO (C)	
4	2024-TO (D)	
5	2024-TO (E)	

D. Nomenclature and Heat Treatment

A= Annealed standard sized (448 x 448 x 2.7 mm) specimen formed till fracture up to the depth of 85 mm

B= Annealed standard sized specimen formed till fracture up to the depth of 93 mm

C= Annealed standard sized specimen formed till fracture up to the depth of 105 mm

D= Annealed standard sized specimen formed up to the depth of 140 mm without fracture

E=Annealed unformed Specimen (Aluminum 2024-TO)

III. RESULTS

A. Tensile Strength

Tensile test of annealed (TO) specimens was carried out to investigate the strength and percentage elongation of Aluminum 2024 at different tempers; its results are as follow:

TABLE V
TENSILE TEST OF ALUMINUM 2024

Samples	Tensile Strength (MPa)	Percentage Elongation
1	208	23.13
2	210	21.61
3	213	22.73

Elongation percentage of the samples was determined by installing extensometer during tension testing. Experimental values of strength and percentage elongation show concurrence with theoretical values quoted in literature. Strength of the alloy increases as a result of cold working while percentage elongation decreases. The mechanical data of the alloy was utilized during the cold forming process. The tensile test graph indicates the trend in mechanical strength and percentage elongation of the specimens.

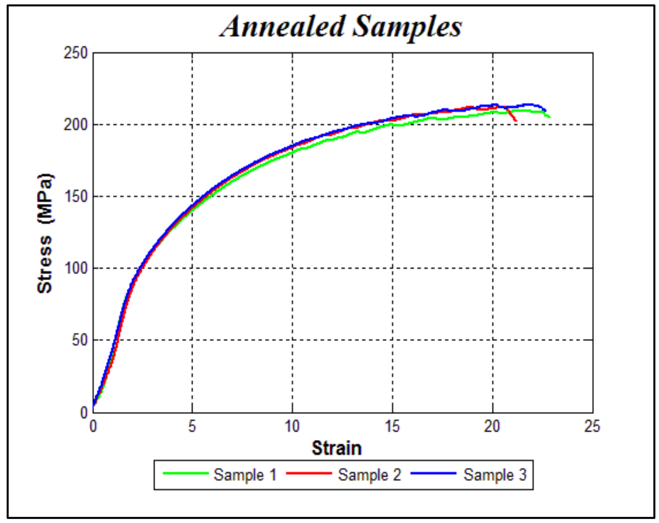

Fig. 2. Stress-Strain curves for T-O samples

AA-2024 alloy shows excellent tensile strength in aged temper with an elongation percentage up to as 10%. Annealing results in drop of 50-60% tensile strength with 50-60% increment in ductility. Annealed (TO) temper is recommended for forming of the alloy.

B. Hardness

Hardness of the alloy exhibits its resistance to indentation. Cold working results in strain hardening consequently increasing the hardness values. Hardness of aged tempers is higher than annealed tempers due to formation of precipitates. Hardness values for different specimens are listed below:

TABLE VI
HARDNESS OF SPECIMENS

Sr. NO	Samples	No. of Samples	Hardness (HV)
1	A	3	68-75
2	B	3	68-75
3	C	3	68-75
4	D	3	68-75
5	E	3	66-72
6	F	3	52-68

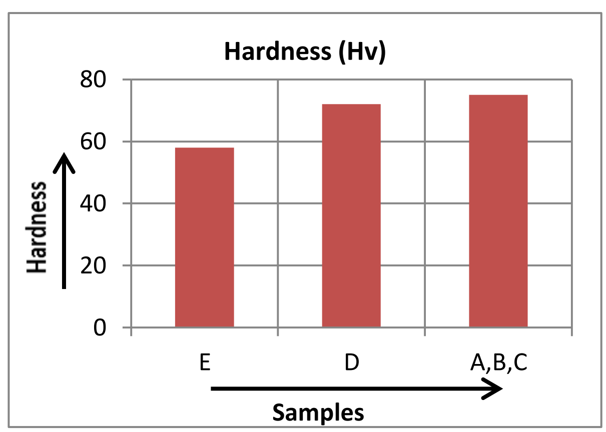

Fig. 3. Hardness data for all samples

It can be observed from the above results that hardness values for all fractured annealed samples (A,B,C) is same, i.e. all the specimens showed maximum strain hardening till fracture. The increment in hardness values is attributed to forming (cold working) operation. Strain hardening increases the hardness and strength of the alloy while compromising its ductility.

C. Thickness Profile

Thickness of the initial stock and formed hemispheres was measured to analyze the flow behavior of Aluminum 2024. Thickness values observed for different specimens are listed below:

TABLE VII
THICKNESS VARIATION IN FORMED SPECIMENS

Sr. NO	Samples	Initial Thickness (mm)	Final Thickness (mm)
1	A	2.65-2.70	1.80-1.98
2	B	2.65-2.70	1.91-2.02
3	C	2.65-2.70	2.05 -2.2
4	D	2.65-2.70	2.30-2.45

The variation in thickness is a direct manifestation of material flow. Uniform material flow results in less thickness variation while non-uniform material flow yields in thinning of sheets. Sample B, B and C show a drastic decrease in thickness of the samples at the center. The thickness decrement resulted in fracture at the center of hemisphere. Sample E showed least variation of thickness in T-O temper. This was achieved by maneuvering the material flow.

IV. DISCUSSION

Precipitation hardened Aluminum alloys are usually formed in T-O (annealed) condition because of their minimized ductility in aged tempers (T-6 & T-8). Current work encompasses the forming of Aluminum 2024 in T-O temper. Annealed tempers showed 23-26 % elongation prior to fracture.

Finite element Analysis was performed to predict and analyze the material behavior during forming operation. Thickness reduction, fracture location and area under maximum load were predicted via FE analysis. Issue of material flow was also catered by analyzing FE results. The experimental values are in accordance with the literature and FE analysis.

A. FE Analysis

The blank was modeled with 8-node PLANE183 axisymmetric elements with a mesh size of 1 mm. The bench, blank holder as well as the punch was modeled with rigid TARGE169 elements while the corresponding surface on blank was modeled with CONTA172 elements. The schematic of the axisymmetric model of process is shown in Fig 4. While Fig. 5 shows the FE model of the complete setup. The load exerted by the blank-holder on the blank has the effect of reducing the metal flow into the central portion due to increased frictional resistance. The effect was modeled by increasing the coefficient of friction between blank-holder and blank surfaces. Additionally, the friction between punch and blank was altered to control the material flow from the center of the blank and in turn control the drastic thinning of the blank.

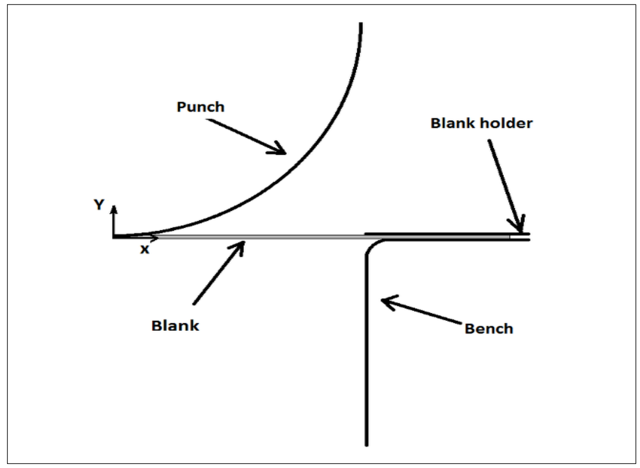

Fig. 4. Axisymmetric representation of the forming process

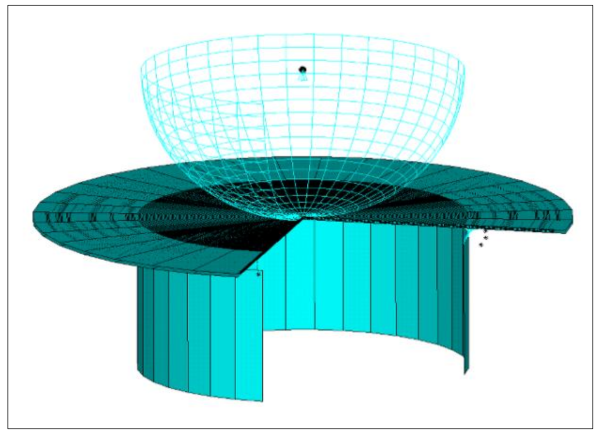

Fig. 5. Finite Element Model for forming simulation

Two cases were analyzed and compared using FE simulations. Case I corresponds to prevailing test conditions in samples A to C where a high clamping force was modeled by a friction coefficient of 1, while low friction between punch and blank, due to presence of lubrication, was modeled by a rather low friction coefficient of 0.1. Case II in Fig. 6 represents the file test case where the reduced clamping force was modeled by a friction coefficient of 0.1 while the friction between blank and press was increase by setting friction coefficient equal to 0.3.

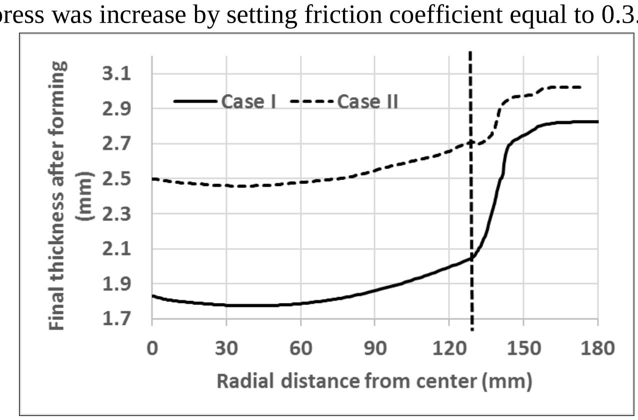

Fig. 6. Thickness reduction of the blank due to forming with different friction conditions

Fig. 6 shows the thickness reduction for both cases as a function of distance from the center. The reduction in thickness as the center closely matches to that observed in experiments, Table VII. It is clearly seen that the reduction in clamp force and increased friction at the center cause the material flow to be much more uniform; resulting in low strain levels. Thus allow greater forming depths as validated by experimental data. The vertical line in Fig. 6 marks the edge of bench. To the right of the vertical line, the material is under the blank holder and moving radially inwards where the circumferential length of the section is decreasing. The result is that the material experiences an increase in thickness to maintain its volume. This phenomenon can be seen to the right of the vertical line in Fig. 8 with an increase in thickness. Again, since case II allows more material flow, the thickness increase under the blank-holder is higher compared to case I.

B. *Experimental Results*

Thickness reduction is directly associated with material flow. Lesser the material flow higher is the thickness reduction at surface under force. Results show the thickness variation in different sheets formed to different depths. All the fractured specimens show a constant increment in hardness up till fracture due to strain hardening, i.e. all fractured specimens reached their maximum ductility limit prior to fracture. Variation in formed depth doesn't directly relate to ductility of the alloy. It refers to discrepancy in material flow, i.e. specimen formed up till 140 mm depth showed a thickness variation of 0.4 mm (low strain) while that formed till 85 mm depth showed a variation of 0.9 mm (comparatively higher strain after fracture). Strain hardening occurred in the sheets due to excessive loads and high strain rates.

The above results indicate that the material flow from the edges was facilitated by applying Molykote on edges only keeping the center intact to allow maximum friction between punch and stock. Spacers also aided in material flow from the edges which was initially being impeded by excessive clamping force, i.e. spacers reduced the clamping force of stock. Grains get elongated and stressed by cold working operations. Cold worked grains have higher strength and lower ductility making them comparatively brittle than the parent alloy. Intermediate annealing before any significant thinning refines the microstructure and restores the ductility while it doesn't show any significant increase in ductility after the structure has undergone permanent irreversible deformation. The experimental results were in accordance with the FE results. FE results were validated by incorporating necessary modifications in the forming setup, i.e. positioning of spacers for higher material flow and application of Molykote to facilitate controlled friction.

V. CONCLUSION

Forming of Aluminum 2024 (T-O) was carried out on conventional press. Process parameters were varied based on the FE analysis to enhance the material flow and formability of the alloy using this particular press. Experimental results showed the improvement in material flow and formability of the alloy by using spacers, intermediate annealing and Modifying the Molykote application.

It is evident from the results that spacers enhanced the forming limit up to 20% of original limit. Intermediate annealing increased the limit up to 10% of the original limit and Molykote modification improved the forming limit up to 50%.

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