ISRES Publishing

The Eurasia Proceedings of Science, Technology, Engineering and Mathematics (EPSTEM)
ISSN: 2602-3199

The Eurasia Proceedings of Science, Technology, Engineering and Mathematics (EPSTEM), 2026

Volume 40, Pages 330-340

ICBAST 2026: International Conference on Basic Sciences and Technology

Numerical Analysis and Optimization of Hydroforming Parameters of a 2024-T3 Aluminum Alloy Interface Part for Aerospace Applications

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Abstract: This study investigates the production of a 2024-T3 aluminum alloy interface component, designed for the mounting of a commercial antenna onto a helicopter tail, using the hydroforming process. Hydroforming is a widely utilized sheet metal forming technique in aerospace applications, operating on the principle of utilizing high fluid pressure to induce plastic deformation of the blank into a male or female die. Compared to conventional forming methods, it enables the production of complex geometries with superior quality. Within the scope of this work, the interface part was first designed to conform to the surfaces of both the antenna and the helicopter tail, followed by the development of the female hydroforming die geometry. The effects of critical process parameters, such as fluid pressure, blank holder force (BHF), and initial blank dimensions, on thinning and stress distribution were examined through Finite Element Analysis (FEA) based on the Forming Limit Diagram (FLD) and material hardening criteria. Through iterative simulations, the optimal process parameters required to prevent potential failure modes, such as tearing and wrinkling, were identified. The results indicate that fluid pressures reaching 50 MPa are necessary for successful forming, with a minimum achievable corner radius of 22 mm. Consequently, it is demonstrated that 2024-T3 alloy can be effectively formed into complex aerospace components using the hydroforming method.

Keywords: Interface, Hydroforming, Die, Press, Sheet metal

Introduction

In the literature, the hydroforming (hydraulic forming) process, also referred to as fluid forming, flexible die forming, or rubber diaphragm forming, is defined as the forming of sheet or tubular metallic materials in a closed container by means of a fluid medium (water, viscous fluid, polymeric material, etc.) that acts as a male or female die. Due to the incompressible nature of the fluid, materials are formed by the effect of the pressure generated during the forming process (Altan, 2006; Singh, 2003; Zhang et al., 2004). This method, which first emerged in the 1890s with initial research conducted in the aerospace sector in Germany and in various fields in Japan, did not receive sufficient attention until the 1990s due to certain technical difficulties. Today, however, thanks to advancements in computer control and hydraulic systems (Karaağaç & Özdemir, 2011; Koç & Cora, 2008), its use is rapidly increasing, particularly in the automotive industry (Karaağaç & Özdemir, 2013; Kılıç & Öztürk, 2016; Özek & Taşdemir, 2017). In the hydroforming process, which provides many advantages over conventional forming and welded joining methods, sheets of different thicknesses can be formed with a single die; precise die matching is not required, and dies can be manufactured using lower-grade materials. Consequently, tooling costs are reduced by up to 90%. Furthermore, because the fluid applies a uniformly distributed load across the entire surface of the sheet and reduces friction between the sheet metal and the die, thereby decreasing local stress

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concentrations (tensile force), thinning in the sheet metal is minimized, and a uniform thickness distribution is achieved (Kandil, 2003; Zhang, 1999; Zhang & Danckert, 1998). As a result of these effects, difficult-to-form and complex parts can be produced at a lower cost, in fewer stages, and with higher strength and dimensional accuracy (Ankaralı et al., 2020; Zhang et al., 2004).

In female die sheet hydroforming (Figure 1), which is a type of the hydroforming process, only a female die is present, and the high-pressure fluid acts as the punch (Önder & Tekkaya, 2008). In this method, after the sheet material is placed on the die and the blank holder is closed, fluid pressure is applied through an integrated channel. To prevent fluid leakage during forming, the blank holder force must be regulated against the applied pressure (Groche & Metz, 2006). From an engineering perspective, the Finite Element Method (FEM) is widely used to verify the functionality of the product and the suitability of the production process prior to actual manufacturing (Şanay, 2010). A review of the literature reveals that while there are numerous studies conducted with male dies (Khandeparkar & Liewald, 2008; Palumbo et al., 2004a; Qin & Balendra, 2004; Wu et al., 2004), studies related to female dies remain relatively limited. Palumbo et al. (2004a, 2004b) performed FEM simulations on the production of complex (cylindrical, square, and compound) geometries using a female die and investigated the failure zones at the corner radii. Kleiner et al. (2004) stated that this method provides high shape and dimensional accuracy; however, they revealed that the friction generated between the sheet and the die with increasing pressure creates a disadvantage in the forming of deep parts.

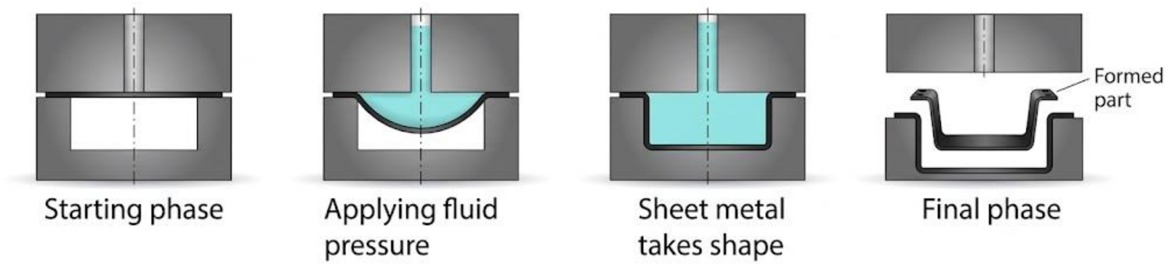

Figure 1. Stages of the hydroforming process.

In the hydromechanical forming method, numerous developments have been made in the literature to increase formability (the limiting drawing ratio). Lang et al. (2009), Verma & Chandra (2006), and Hatipoğlu (2007) demonstrated that by applying pre-bulging pressure, the material's resistance to tearing can be increased through strain hardening. Kandil (2003), Dachang et al. (2005), Abedrabbo et al. (2007), Lang et al. (2004), and Khandeparkar & Liewald (2008) conducted various studies on determining the optimum parameters for a successful forming process; while Zhang et al. (2003) and Lang et al. (2004) analyzed the effects of these parameters through numerical simulations. Using fluid pressure instead of a blank holder to reduce friction (Shirizly et al., 1994; Tirosh et al., 1996; Zhang & Danckert, 1998), hydrodynamic deep drawing which allows high-speed fluid flow (Hsu & Hsieh, 1996; Pennington, 1996), the use of radial fluid pressure (Lang et al., 2004; Yang et al., 1995), active material flow control via drawbeads (Siegert et al., 2000), and the use of viscous fluid (Liu et al., 2000) are other prominent innovative approaches.

While adjusting a male die is a demanding process, forming with a female die can be controlled with fixed parameters and simpler hydraulic systems. However, in this method as well, as the sheet material comes into contact with the female die, friction increases, and localized thinning occurs. In this study, it is aimed to produce sheet metal products, which are conventionally manufactured in multiple stages by deep drawing, in fewer stages, rapidly, and economically. For this purpose, the design and manufacturing of hydroforming dies were carried out to minimize the friction between the sheet and the die and to achieve a much more uniform thickness distribution in the part by making the entire die movable in the female die sheet hydroforming process.

Materials and Methods

For the interface design, SolidWorks 2021 was utilized during the design phase, while the commercial software LS-DYNA was employed for the analysis phase. The interface was designed for the Ga-58 commercial antenna, whose technical drawing is presented in Figure 2. The antenna was modeled in a CAD environment. Subsequently, the interface design phase was carried out in accordance with its base dimensions.

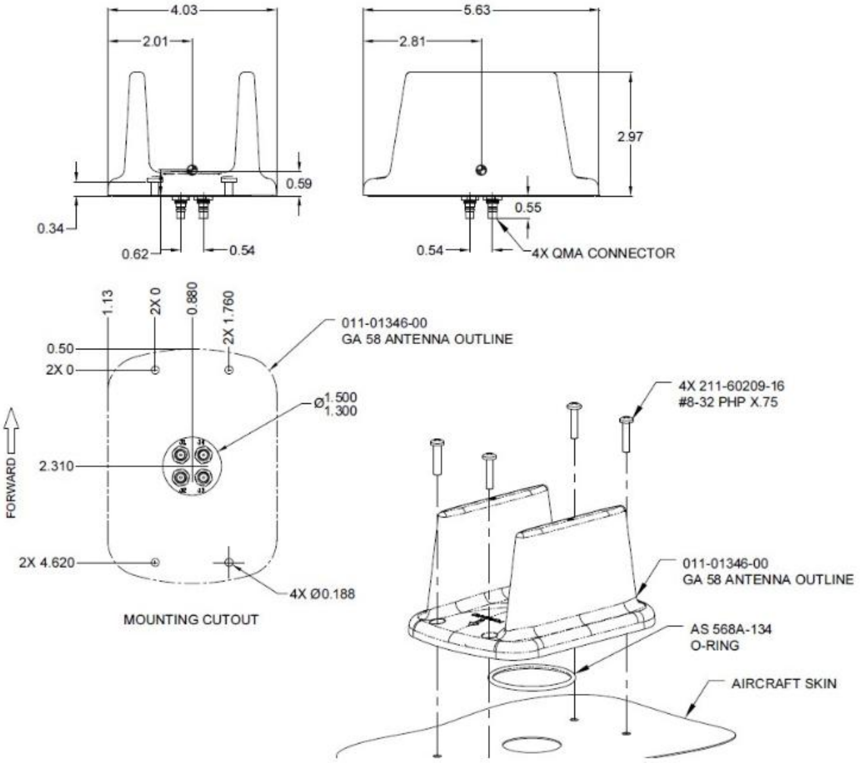

Figure 2. Technical drawing of the Ga-58 commercial antenna (Faders, 2018).

In the interface design, mounting on a helicopter tail with a diameter of 1000 mm and an inclination of 10 degrees was taken into consideration. The part, designed with a thickness of 1 mm, is fastened to the antenna using bolts. The mounting on the tail side, on the other hand, will be carried out using 3.2 mm rivets. In accordance with generally accepted manufacturing rules, the arrangement was configured such that the rivet edge distance is 2D+1, the distance to the radius is D+1, and the distance between two rivets (rivet pitch) is between 4D and 6D, where D is the rivet diameter. The general dimensions of the designed interface part are presented in Figure 3.

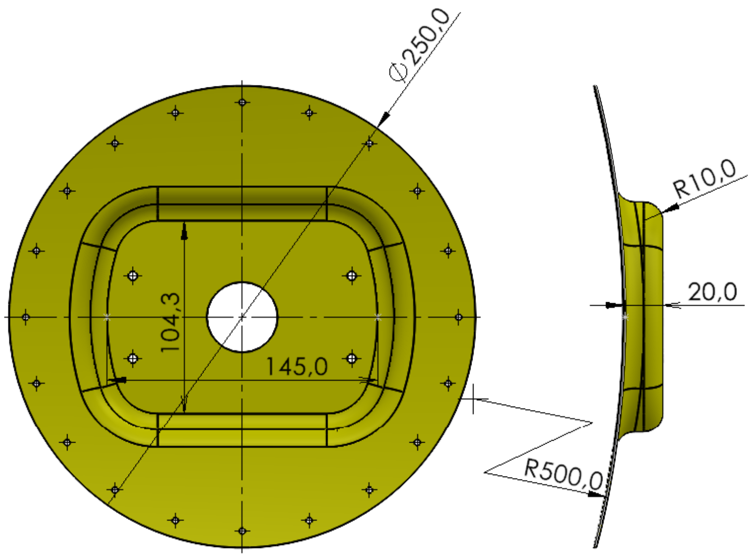

Figure 3. Technical drawing of the designed interface part.

Following the design of the interface part, the die and blank holder required to achieve its geometry were designed. In order to obtain the flange geometry of the part, which will fit onto the helicopter fuselage, by forming it between the die and the blank holder, the die geometries were determined in accordance with the flange geometry (Figure 4).

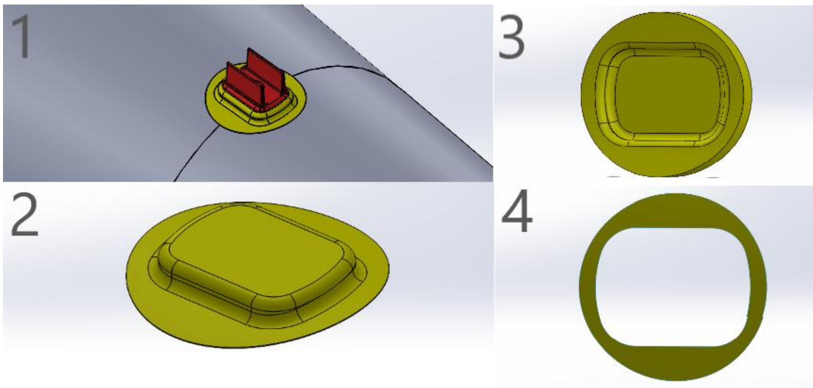

Figure 4. Die, blank holder, and interface designs.

2024-T3 was selected as the material for the interface part. Some mechanical properties of 2024-T3 are presented in Table 1.

Table 1. Mechanical properties of 2024-T3 (ASM Material Data, n.d.)

Yield Strength	345 MPa
Tensile Strength	483 MPa
Density	2.78g/cm^3
Modulus of Elasticity	73.1 GPa
Poisson's Ratio	0.33
Strain Hardening Exponent	0.16
Strength Coefficient	690 MPa

The strain hardening exponent and strength coefficient are material properties used in cold forming methods. They are derived to describe the plastic flow region of the stress-strain curve. This derived expression is called the "Hollomon Equation". The strain hardening exponent represents a material's capability to strain harden. Its high values indicate that the material has a ductile structure and is capable of strain hardening. The strength coefficient, on the other hand, provides information about the hardness of the material. It determines the material's resistance to plastic deformation.

Following the design phase, forming analyses were conducted using the LS-DYNA software. Initially, the geometries of the die, blank holder, and sheet metal part were prepared for analysis. While keeping the material thickness and hydraulic pressure values constant, the effects of blank holder forces of 20, 30, 40, 80, 120, and 160 kN, along with coefficient of friction parameters of 0.05, 0.1, and 0.17 established within the program, on the thinning of the sheet were investigated.

Results and Discussion

When the analyses conducted in the FEA model, which was established for the hydroforming of the interface part designed to ensure the integration of the Ga-58 commercial antenna into the helicopter tail, were executed, the pressure values at which the sheet metal part took the shape of the die and the resulting percentage thinning amounts in the sheet are presented in Table 2. The variation in percentage thinning with blank holder force at different coefficients of friction is given in Figure 5.

The maximum thinning in the part occurs at the bottom corners, as shown in Figure 6. As can be understood from Figure 5, the most significant factor affecting the thinning of the part is the coefficient of friction. As the coefficient of friction increases (from 0.05 to 0.17), the flow of the sheet metal into the die becomes more difficult, and the material is forced to stretch. At a friction of 0.05, the thinning rates remain at a relatively low level (13.1%–14.8%). At a friction of 0.10, the thinning rates began to increase and were observed between 15.9% and 18.5%. The high friction at 0.17 caused excessive straining of the material, and the thinning rates rose up to 30%, increasing the risk of tearing to the maximum level. The increase in the blank holder force creates a holding effect that restricts the flow of the material in the flange region into the die. Especially in cases where friction is high (0.17), increasing the blank holder force from 20 kN to 160 kN significantly increased the thinning from 19.6% to 30.1%. In cases where friction is low (0.05), the increase in blank holder force had a relatively smaller effect on thinning.

Table 2. Analysis results

No	Blank Holder Force (kN)	Coefficient of Friction	Pressure (MPa)	Thickness (mm)	Thinning (%)
1-	20	0.05	57.14	0.868	13.182
2-	30	0.05	57.14	0.866	13.359
3-	40	0.05	60.71	0.851	14.863
4-	80	0.05	60.71	0.858	14.116
5-	120	0.05	60.71	0.855	14.491
6-	160	0.05	57.14	0.856	14.372
7-	20	0.1	60.71	0.840	15.995
8-	30	0.1	60.71	0.829	17.086
9-	40	0.1	60.71	0.872	17.275
10-	80	0.1	60.71	0.826	17.341
11-	120	0.1	60.71	0.819	18.114
12-	160	0.1	60.71	0.814	18.573
13-	20	0.17	57.14	0.803	19.623
14-	30	0.17	60.71	0.794	20.570
15-	40	0.17	60.71	0.790	20.961
16-	80	0.17	60.71	0.784	21.537
17-	120	0.17	60.71	0.744	25.538
18-	160	0.17	60.71	0.698	30.147

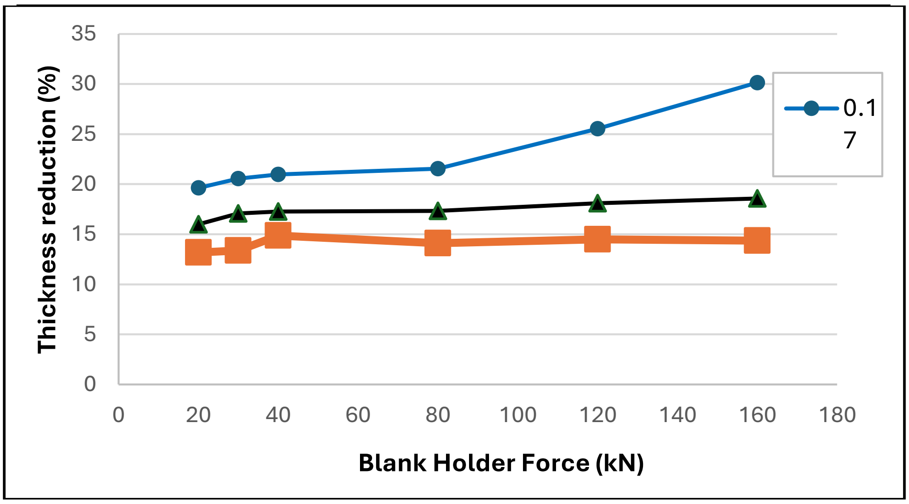

Figure 5. Effect of blank holder force on percentage thinning.

It has been stated by Halkacı et al. (2014) that a coefficient of friction of 0.05 between aluminum material and steel dies corresponds to experimental results. Therefore, the analysis results conducted with a coefficient of friction of 0.05 were taken into consideration when selecting the most suitable parameters. According to the blank holder force values tested, all force values in the range of 20 kN to 160 kN yielded nearly the same thinning values. However, when the blank holder force is low, there may be a risk of wrinkling in the sheet metal part. Therefore, the parts were evaluated for wrinkling at different force values using Isophote Analysis; according to the results obtained in Figure 6, it was observed that wrinkling in the flange region of the sheet metal part decreased at a force value of 120 kN, and thus it was considered the optimum value. Consequently, it was determined that a fluid pressure of 60 MPa and a blank holder force of 120 kN must be applied to form a part with an initial blank diameter of 230 mm and a bottom radius of 10 mm.

The FLD (Forming Limit Diagram) showing the forming limits of the 2024-T3 material was obtained from the study by Lee et al. (1997), as seen in Figure 7. Accordingly, it was concluded that the highest thinning in the material reached approximately 11% in the plane strain state, where the formability is at its lowest and the minor strain value is zero. Based on the thinning results obtained with a 10 mm bottom radius as shown in Figure 8, it was evaluated that it would not be possible to successfully produce the part with this selected radius value. Therefore, the part design has been updated.

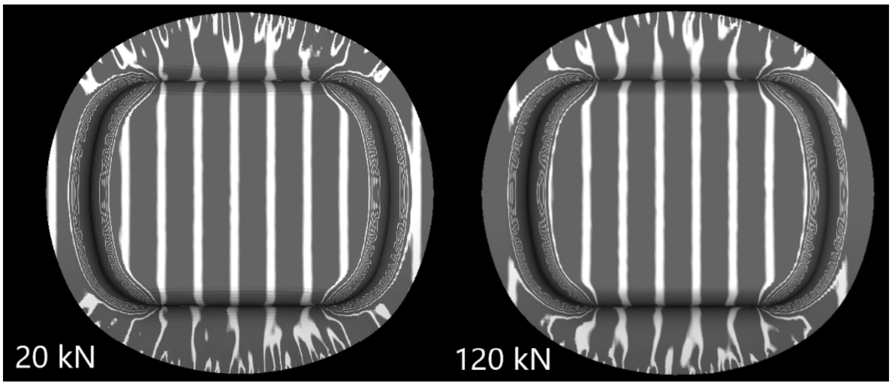

Figure 6. Isophote analysis for different blank holder forces.

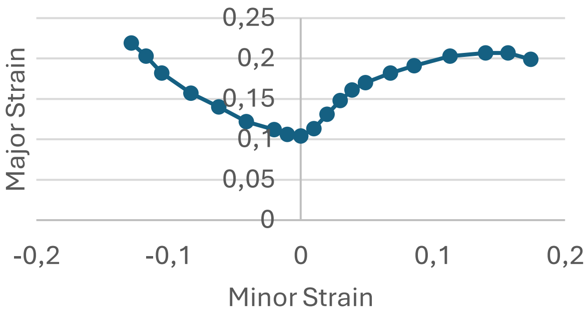

Figure 7. FLD of 2024-T3 aluminum material (Lee et al., 1997).

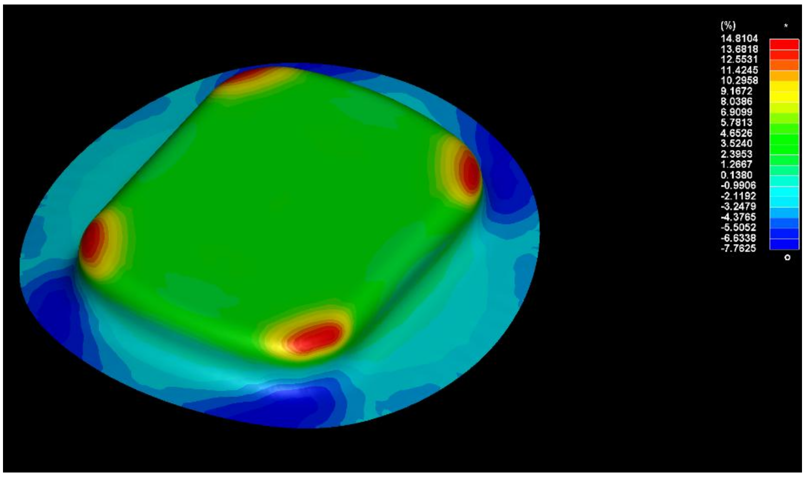

Figure 8. Thinning contours occurring at the base of the part.

Analyses were repeated for the case with the new diameter, a coefficient of friction of 0.05, and a blank holder force of 120 kN. In determining the new bottom radius value, the 600 kN clamping force of the hydroforming press located in the Hydroforming Laboratory at Konya Technical University, where the part will be produced, was also taken into consideration. During forming, forces resulting from fluid pressure and blank holder force act on the surface area of the female die. These forces must not exceed the capacity of the press used in the manufacturing process. According to the analysis results shown in Figure 9, when the vertical force distribution on the die reached the 600 kN limit (s=0.007); upon examining the cross-section of the die, sheet, and blank holder as shown in Figure 10, it was observed that the sheet had not yet seated in the female die and the desired geometry could not be achieved. In this case, it was determined that the part bottom radius should be 22 mm when the die is subjected to a 600 kN limit force. It was determined through analyses that for a part with a 22 mm bottom radius, the initial blank diameter must be 260 mm to maintain a minimum flange distance of 11.6 mm (3D+2, D=3.2) between the sheet edge and the part entry radius. In the new analysis, when the force-time graph acting on the die shared in Figure 11 for the case of an initial blank diameter of 260 mm and a radius of R=22 mm was examined, it was observed that the sheet metal part fully seated in the female die as shown in Figure 12, confirming that these parameters are suitable for manufacturing.

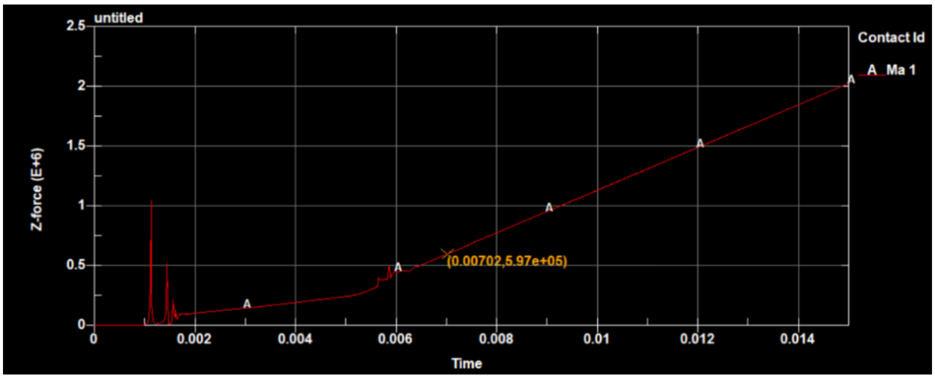

Figure 9. Time-force graph before the geometry update.

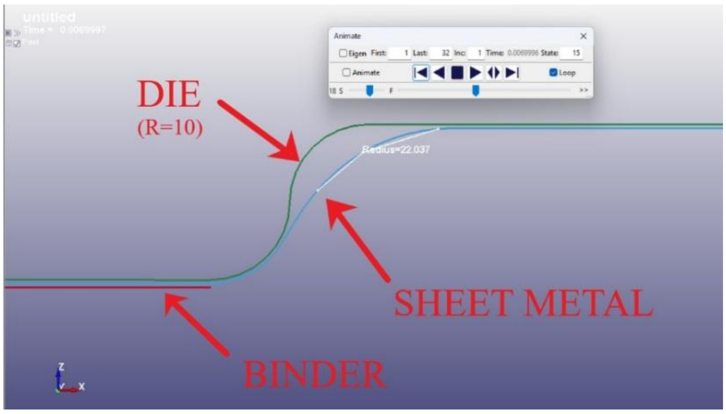

Figure 10. State of the sheet at the 60-ton limit before the geometry update.

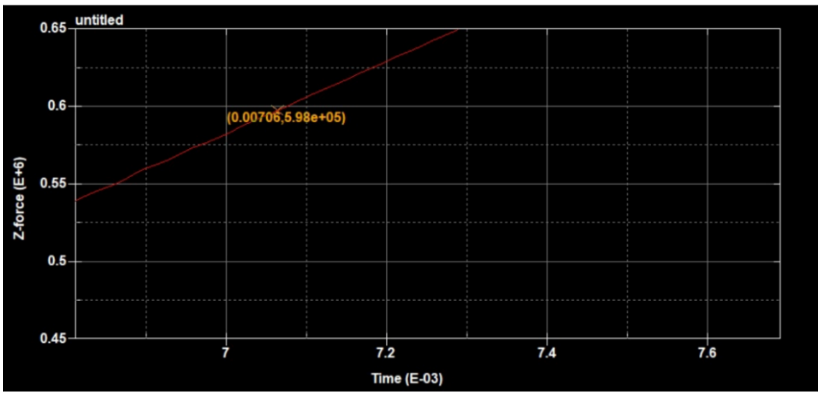

Figure 11. Force-time graph for the new analysis.

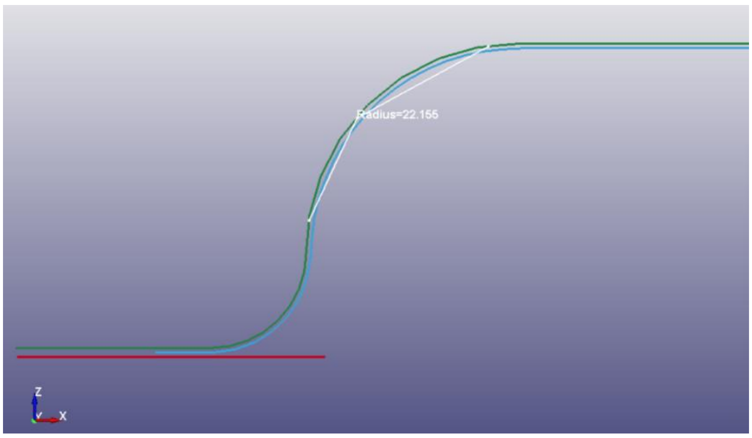

Figure 12. Final shape of the sheet in the analysis with an initial blank diameter of 260 mm and a bottom radius of 22 mm.

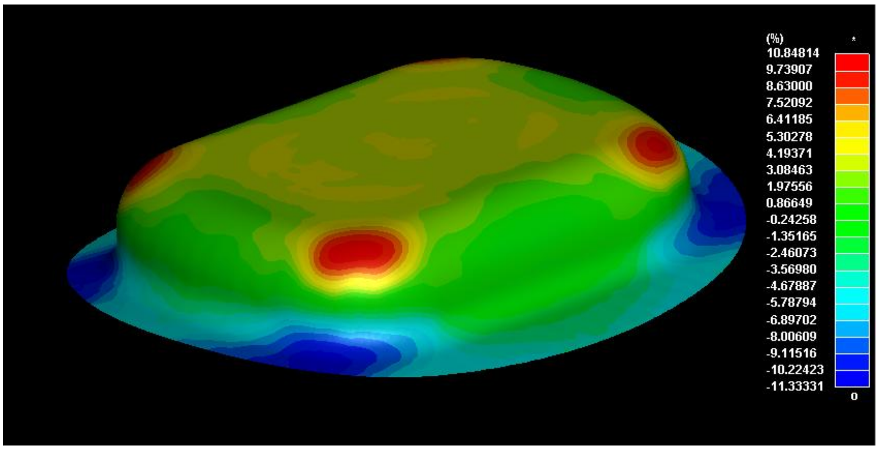

Figure 13. Thinning state determined in the final geometry.

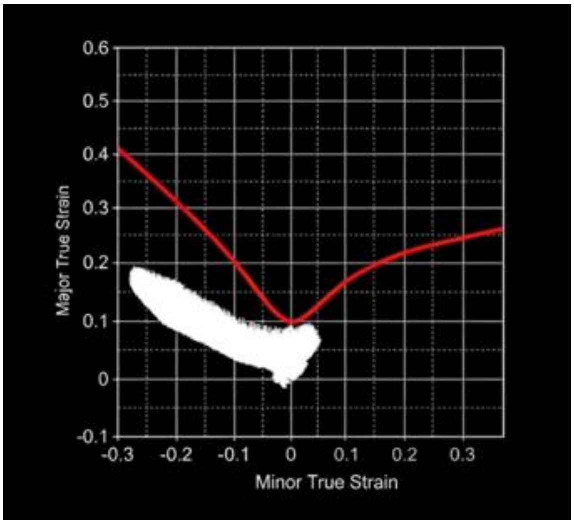

Figure 14. FLD (Forming Limit Diagram) for the updated geometry.

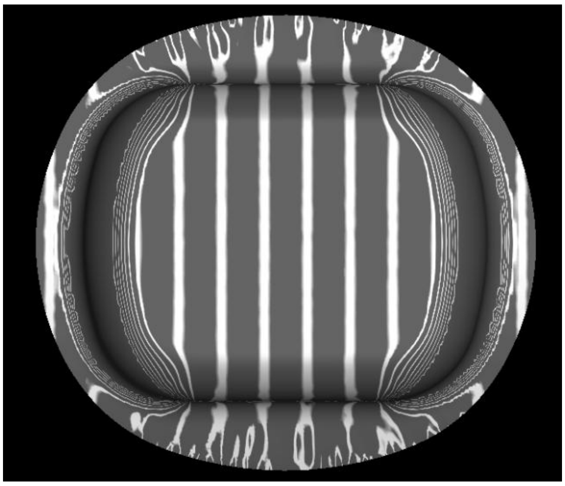

Figure 15. Isophote wrinkling analysis of the final geometry.

In conclusion, it was observed in the analyses conducted using the die with a bottom radius of 22 mm, 2024-T3 material with an initial blank diameter of 260 mm, and a blank holder force of 120 kN, that the sheet fully seated in the die. As shown in Figure 13, at a pressure of 6.75 MPa, the thinning value remained below 11%. When the strain distribution obtained from the part was plotted on the FLD of the material, as seen in Figure 14, all strain values remained below the forming limit curve. Therefore, it was concluded that the sheet metal part can be formed without failure using the identified parameters, and the part can be produced with an acceptable level of wrinkling in the outer flange diameter region according to the Isophote analysis in Figure 15. Thus, an interface part that can be used for the connection of the Ga-58 commercial antenna to the helicopter tail has been designed, and the parameters for the successful production of the part through the hydroforming process have been determined.

Conclusion

In this study, the manufacturability of an interface part designed from 2024-T3 aluminum alloy to ensure the integration of the Ga-58 commercial antenna into the helicopter tail was investigated using the hydroforming method with a female die through Finite Element Analysis (FEA), and the process parameters were optimized. As a result of the iterative analyses conducted, the following key findings were obtained:

Effect of Friction and Blank Holder Force: It was observed that the most significant factor affecting the thinning of the sheet is the coefficient of friction. An increase in the coefficient of friction restricts the material flow into the die, thereby increasing the risk of tearing. Consistent with the literature, the most suitable coefficient of friction for the aluminum-steel interface was evaluated as 0.05. The optimum blank holder force that minimizes wrinkling defects (Isophote analysis) in the flange region was determined to be 120 kN.

Die Geometry and Press Capacity Constraints: In the analyses conducted with the initial design of a 10 mm bottom radius and a 230 mm initial blank diameter, it was observed that the maximum thinning in the part exceeded the 11% safe forming limit in the Forming Limit Diagram (FLD) of the 2024-T3 material. Additionally, under these parameters, the limits of the available hydroforming press with a 600 kN capacity were reached before the part could fully take its shape. This situation necessitated a revision in the part geometry.

Optimization and Successful Forming: Considering the press capacity and FLD limits, the part bottom radius was increased to 22 mm, and the initial blank diameter to 260 mm. In this optimized new design, analyses conducted under 33.75 MPa fluid pressure and 120 kN blank holder force showed that the sheet metal part fully seated in the die, the press limit force was not exceeded, and wrinkling remained at a tolerable level. Most importantly, the maximum thinning value remained below 11%, and all strain distributions were located within the safe zone of the FLD curve.

In conclusion, it has been proven that the 2024-T3 aluminum alloy, which is preferred in the aerospace industry due to its high strength but is difficult to form, can be successfully produced without tearing and wrinkling defects using the hydroforming method when proper die design and optimized process parameters are utilized. This study demonstrates that complex aerospace interface parts can be safely produced in fewer stages through hydroforming, instead of multi-stage conventional methods.

Scientific Ethics Declaration

* The authors declare that the scientific ethical and legal responsibility of this article published in EPSTEM journal belongs to the author.

Conflict of Interest

* The authors declare that they have no conflicts of interest.

Funding

* This work was supported by Turkish Aerospace Industries (TUSAŞ).

Acknowledgements or Notes

* This article was presented as an oral presentation at the International Conference on Basic Sciences and Technology (www.icbast.net) held in Konya/Türkiye on April 02-05, 2026.
* The authors would like to thank the Hydroforming Laboratory at Konya Technical University for their support during the analysis process.

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To cite this article:

Ture, C., Katırcı, B., & Turkoz, M. (2026). Numerical analysis and optimization of hydroforming parameters of a 2024-T3 aluminum alloy interface part for aerospace applications. *The Eurasia Proceedings of Science, Technology, Engineering and Mathematics (EPSTEM), 40,* 330-340.