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Experimental Investigation of The Manufacturability of The Rear Cargo Door Actuation Cavity Component in Airbus A321 Aircraft Using Hydroforming Method with Al 2024 T3 Material

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Abstract

Hydroforming is a process for shaping metal sheet materials using high-pressure fluid, which is gaining importance and becoming more widely used every day. Due to the incompressibility of liquids, the same pressure is applied at every point, allowing for the easier creation of complex shapes. This method enables the production of higher-strength parts as a single piece. It is possible to manufacture many components using hydroforming without the use of expensive tooling costs, additional expenses, and weight-adding fasteners.

In this study, design and finite element method (FEM) analyses were performed for the production of the rear cargo door actuation cavity in Airbus A321 passenger aircraft, followed by mold design and production. Suitable shaping was achieved using fluid at a pressure of 1600 psi (110 bar). A commercial hand pump was used to obtain the required pressure. The material used was 1.2 mm thick Al 2024 T3. The produced sheet material was examined using non-destructive testing methods to ensure it met the necessary quality requirements. The results of the simulation and experimental studies of the product shaped by hydroforming were compared, and the results were found to be highly compatible.

The study demonstrated that hydroforming technology could be used in the production of more complex workpieces that require higher strength, thanks to the more controllable and precise force application in later stages. Guiding results were obtained regarding material and pressure selection for the production of the rear cargo door actuation cavity in Airbus A321 passenger aircraft.

This study was produced from the master's thesis of Ahmet ARZUMAN, under the supervision of Assoc. Prof. Dr. Mustafa SOYLAK.

1. Introduction

The use of fluids in metal forming has a history spanning over 100 years. Studies on hydroforming technology began in the 1940s. Hydroforming is a forming method in which the stress force created by pressurized fluid in a closed environment is used to shape the material, allowing sheet or tube materials to be formed with the help of a mold. Hydroforming is a metal forming process that uses fluid pressure instead of traditional mechanical systems to create complex shapes, achieving a near-net shape final form. Most technological advancements in this field occurred after 1950. Between 1900 and 1950, hydroforming was primarily used for the production of steam boilers, musical instruments, and prosthetic limbs. Afterward, from 1950 to 1985, it was mainly employed in the plumbing industry for the production of copper T-joints and in bicycle frame manufacturing. Significant advancements in hydroforming methods and equipment occurred during this period due to its commercial potential. Hydroforming became a highly practical and cost-effective manufacturing technique when applied to the right products.

It was used in the aerospace industry because it provided an economical process for producing sheet metals. While the mechanical molding technique required expensive and multi-part tools, hydroforming allowed for the mass production of similar products with fewer components. For this reason, hydroforming has been used by aerospace manufacturers like Boeing, Cessna, Bombardier, Airbus, and Embraer for the production of various metal sheet components. Particularly, with the technical advancement provided by forming with rubber-based membranes in hydroforming applications, this technology began to be widely used by many aircraft manufacturers. With sufficient high pressure, the rubber membrane inflates like a balloon with hydraulic pressure, causing the metal sheet to take the shape of the mold it contacts. This significantly reduced the number of components required for mechanical production.

However, hydroforming has two main limitations. The first is that the molding process is longer compared to mechanical

processes. The second limitation is the difficulty in ensuring equal force distribution and sufficient pressure across the entire component, especially in very long parts. During the 1950s, with the improvements made in the materials used for manufacturing pressurized membranes, more flexible membranes were developed to address the imbalance in pressure distribution, led by commercial companies. In the 1960s, hydraulic presses capable of serial operation were introduced for hydroforming. Many commercial companies used hydraulic presses for complex parts, while simpler shapes were created using rubber membrane hydroforming. With this method, it has become possible to create two or more parts as a single piece, eliminating the need for fasteners such as rivets, welding, bolts, or nuts. Complex parts with high strength can be easily produced, achieving high surface quality, reducing scrap, and requiring fewer finishing processes. Since no additional fasteners are used, there is approximately a 30% weight reduction. This technique is used not only in the automotive and aerospace industries but also in the production of household appliances. In the automotive sector, companies such as Ford, GM, BMW, and Audi use parts produced with this technology. Hydroforming technology is widely used, particularly for the production of aluminum components. Additionally, components produced by hydroforming are used in nuclear facilities, oil refineries, and gas turbine engine parts. Hydroforming allows the production of parts up to 4 meters in length and makes it possible to produce large-sized parts without any joints. Hydroforming is a current research topic being studied by scientists.

The researchers researched all the different technologies available for hydroforming processes and compared them with other manufacturing methods (Bell, C., et al., 2020). The other researchers reviewed the latest techniques for sheet and tube hydroforming and drew conclusions regarding the future development potential of hydroforming technology (Lang, L. H., et al., 2004) . Hydroforming process tested and examined using the finite element method (FEM) (Zhang, S., et al., 2003). Researchers observed that deformation decreased when using a movable die. A sample hydroforming process presented by Hein, P., & Vollertsen, F. (Hein, P., & Vollertsen, F.,1999). The hydroforming process based on the use of sheet metal was described, and the current results of research in this area were provided. Numerical simulations and analytical models significantly improved the forming of molded parts, evaluating conditions affecting wrinkling and breakage. Experimental studies confirmed FEM calculations. The thickness distribution of the molded product in the hydroforming process has been examined by researchers (Hwang, Y. M., & Altan, T.,2003). Simulation can provide valuable insights into the design of die shapes and geometries in hydroforming and metal forming processes. Researchers have been summarized their experience in designing hydroforming processes for tubes and sheets using simulation techniques and experiments in their study (Oh, S. et al., 2003). They performed simulations for all hydroforming processes, using the results to predict and correct forming defects such as wrinkling and cracking. Based on this experience, they also proposed necessary improvements in the design process. The results of a tube hydroforming finite element model, developed using the commercial finite element program ABAQUS/Standard, have been presented by the researchers in theri study (Kridli, G., et al., 2003). This paper discusses the effects of initial tube thickness and radius on corner fill and thickness distribution in tubes undergoing hydroforming. They found that using a larger die corner radius reduced thickness distribution differences. Researchers conducted experimental and numerical simulations to investigate the hydroforming of rectangular-section automotive structural parts in their study (Yuan, S., et al., 2006). The study discussed the impact of pressure on cracking and thickness distribution and analyzed damage causes such as rupture and folding. It was found that the maximum thickness occurred at the center of the cross-section edges, while the minimum thickness was observed in the transition zone. Plastic deformation was shown to concentrate in the transition zone between corners and edges. In his study, one of the researchers specifically examined the hydroforming of irregularly shaped and curved parts (Yuan, S.,2022). In his study, Yuan, S. analyzed process data such as dimensional accuracy and sheet thickness distribution for parts produced through hydroforming. Zhang, S. H. discussed developments in hydroforming processes, highlighting types of processes for forming tubular and flat sheets, particularly for automotive applications (Zhang, S. H., 1999).

Researchers provided an overview of hydroforming possibilities for tubes, extrusions, and metal sheets in their study (Siegert, K., et al., 2000). They presented a special molding method designed for presses with multi-point cushion systems derived from deep drawing processes, discussing the possibilities and benefits of hydroforming for shaping tubes, extrusions, and sheet metal. Some researchers explained the fundamentals of tube hydroforming technology, examining various parameters such as tube material properties, pre-die geometry, lubrication, and process controls and their effects on product design and quality. They also investigated the relationship between process variables and achievable part geometries (Ahmetoglu, M., & Altan, T., 2000). A newly developed method for forming hybrid parts combining metal sheets with long fiber-reinforced thermoplastics (LFTs) has been introduced by some researchers in their study (Fang, X., & Kloska, T., 2020). Although the idea of combining two different materials in a single part is not new, most current processes require separate production techniques and additional joining steps for each material. This new process involves composite forming tools for sheet metal and thermoplastics in a single simultaneous operation step, providing a cost- and time-efficient solution for multi-material lightweight structures. In tube hydroforming, it is important to understand the behavior of the tube in response to applied pressure loads. These relationships explained in their work by the researchers, proposing methods to improve process control and emphasizing the importance of process control on the quality of forming results (Dohmann, F., & Hartl, C., 1996). The advantages of the hydroforming technique examined in their study by the other researchers (Lücke, H.U., et al. 2001), discussing the performance of high-volume hydroforming lines processing longitudinally welded aluminum tubes. They analyzed the development of parts suitable for serial production using hydroforming, short development times with optimized process chains, and efficient methods to meet high part quality requirements, highlighting the contributions of simulation studies. The free forming method has been explored in his study by Asnafi, N. (Asnafi, N., 1999). The analytical model developed explained where the limits of free forming lie, how different material and process parameters affect the forming results, and what experimental research in hydroforming should focus on. The important aspects of tube hydroforming technology, such as material selection, friction, pre-design, hydroforming processes and tool design, die

materials, and coatings, determining that the popularity of tube hydroforming in both industry and academia accelerated the path toward high-volume production have been examined by Ahmetoglu, M., et al. (Ahmetoglu, M., et al., 2000). A new sheet hydroforming technique using a movable die has been proposed by the researchers (Zhang, S., et al., 2004). An overview of the latest technologies in hydroforming in terms of semi-finished products, presses, and tool design, briefly introducing new hydroforming techniques such as improved formability of lightweight materials and the use of thermal energy has been provided by Hartl. C. (Hartl, C., 2005) . He also explored the use of heat energy to enhance formability. FEM-based simulations to determine the most suitable load paths for hydroforming structural components using different tube materials have been used by the researchers in their study (Aue-U-Lan, Y., et al., 2004). Experimental and simulation results showed that FEM-based load paths significantly reduced trial-and-error rates in producing complex parts and improved efficiency. The optimal regulation of the load relationship between internal pressure and axial feeding in the high-pressure forming of T-shaped metal tubes investigated by the researchers in ther scientific study (Fann, K. J., & Hsiao, P. Y., 2003) . They developed a program module that controlled the quality of hydroformed tubes through FEM analyses, focusing on thickness integrity and geometric accuracy. An analysis of tube material properties under hydroforming conditions, comparing the results with experimental measurements has been conducted by researchers in their study (Koç, M., & Altan, T., 2001). The materials studied included low-carbon steel 1008, SS 304, and aluminum alloy 6260-T4. Thickness predictions from the analytical model showed good agreement with experimental measurements. The limits of hydroforming, investigating how different material and process parameters affect the loading path and forming results studied by the researchers in their study (Asnafi, N., & Skogsgårdh, A., 000). They found that changes during hydroforming were highly dependent on the geometry of the tube. The analytically obtained tube shape aligned well with experimental results. A customizable method for better control of tube hydroforming processes has been presented by the researchers in theri study (Aydemir, A., et al., 2005). They used specific stability criteria to prevent wrinkling and rupture.

A new optimization technique and FEM simulations to determine the optimal load path for hydroforming processes using closed and T-jointed tubes have been used by the researches in their study (Imaninejad, M., et al. 2005). Their goal was to produce parts with minimal thickness variation while keeping maximum working stress below the material's critical stress during the forming process. Optimized load paths provided better part-to-die fit and greater protrusion heights. A researcher used finite element simulation (LS-DYNA) and optimization software (LS-OPT) to optimize loading paths for closed-die and T-shaped tube hydroforming experiments (Tolazzi, M., 2010). In this study, the goal was to determine the loading paths for achieving a uniform thickness distribution, maximum stress, and the highest possible deformation in the material. An optimization procedure was developed for the hydroforming process based on experimental data and FEM simulations. Tube hydroforming experiments were conducted using the optimized loading paths, and the experimental results showed good agreement with the finite element simulations. The advantages of forming tubes and sheets using hydroforming compared to traditional manufacturing methods like spot welding or welding have been explained by the researchers in their study (Kocańda, A., & Sadłowska, H., 2008). The computer modeling of these processes was demonstrated. The finite element simulations of all hydroforming processes in an automotive system have been presented by Trana, K. (Trana, K., 2002). The focus of this research was on developing practical simulation methods for the hydroforming process and determining how bending and pre-forming processes affect hydroforming results. Good agreement was obtained when comparing simulation and experimental results in terms of sheet thickness distribution.

In this study, the manufacturability of the rear cargo door hinge housing for the Airbus A321 passenger aircraft was tested using experimental and simulation methods. The relatively simple geometry of the component made it a suitable candidate for hydroforming. The component was produced from Al 2024 T3 material. The cross-sectional reduction of the produced component was measured, and crack inspections were performed. When comparing the simulation data with experimental results, compatible outcomes were achieved.

2. Experimental Study

In this study, the design, simulation, and production of the rear cargo door hinge housing for the Airbus A321 aircraft were carried out using the hydroforming method. For the experimental study, a 1.2 mm thick Al 2024 T3 sheet material was used. Al 2024 T3 is a certified sheet material widely used in the aerospace industry. The technical specifications of the material are provided in Table 1.

Table 1. Technical specifications of Al 2024T3.

Chemical Composition (%)	Mechanical Properties (Mpa)	Hardness Value (HB)	Density (g/cm³)	Weldability	Elongation (%)
Silicon (Si) 0.00 - 0.50 Chromium (Cr) 0.00 - 0.10 Manganese (Mn) 0.40 - 1.20 Magnesium (Mg) 0.30 - 0.90 Copper (Cu) 3.80 - 4.90 Titanium (Ti) 0.00 - 0.20 Iron (Fe) 0.00 - 0.50 Zinc (Zn) 0.00 - 0.25 Aluminium (Al) Balance	Yield Strength 290 - 360 Tensile Strength 400 - 485 Shear Strength 283	120	2.78	Moderate Level (Spot Welding is Recommended)	10-16

As part of the study, a mold design was created for conducting the experiments, and it was manufactured using St37 material. The technical specifications of St37 material are provided in Table 2.

Table 2. St37 technical properties.

Chemical Composition (%)	Mechanical Properties (Mpa)	Hardness Value (HB)	Density (g/cm³)	Weldability
C=Max 0.2 Mn=Max 1.4 P=Max 0.04 S=Max0.04 N=Max0.012 Cu=Max0.55	Yield Strength =235 Tensile Strength = 360-510	120-160	7.85	Good

As part of the study, the design of the experimental sample was created in 3D, and this design was subjected to analysis using the finite element method. The commercial software SolidWorks was used during the designing phase, while pressure resistance tests using the finite element method were performed with Ansys software. The design and simulation steps are illustrated in Figure 1.

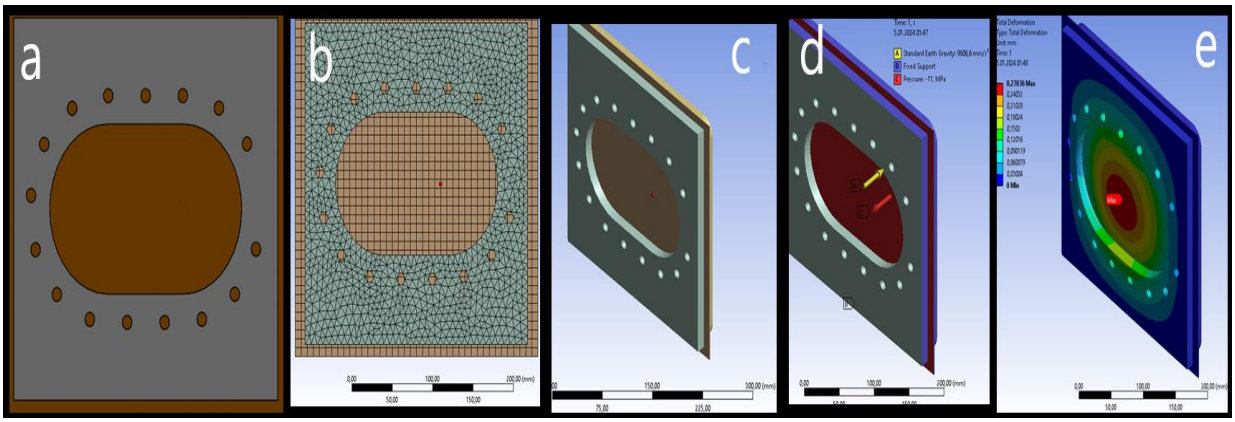


Figure 1. Design and simulation study. a. 3D system component design assembly display, b. Meshing process with the finite element method, c. Model view before the pressure test, d. Pressure test and force display, e. Deformation formation during the simulation and regional pressure distribution display.

As shown in Figure 1-d, a uniform pressure load of 110 bar was applied to the inner surface of the apparatus. Here, A = Gravitational force, B = Fixed component area and C = Pressure distribution representation.

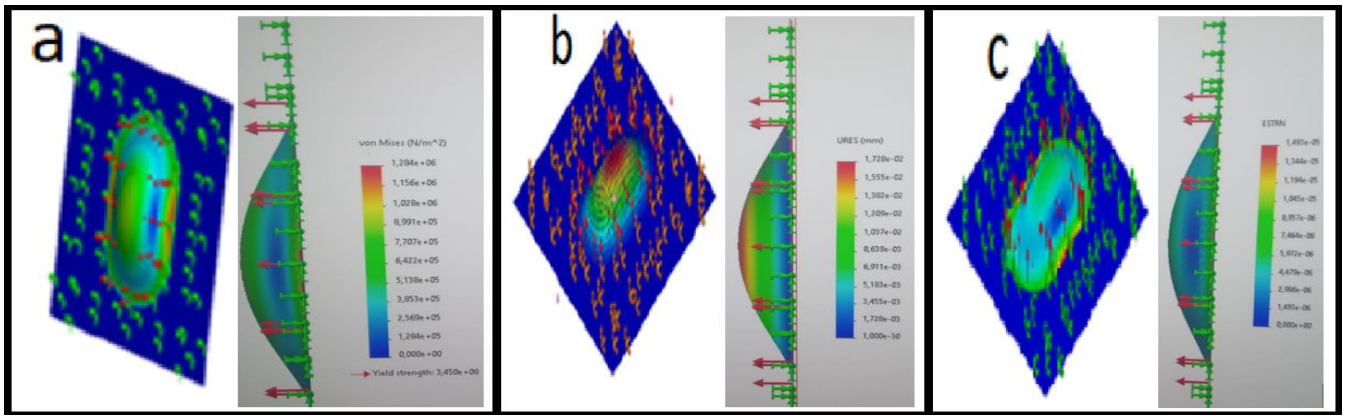


Figure 2. Results obtained in the simulation study. a. Stress, b. Displacement, c. Strain.

Simulation studies (Figure 2.) show that the highest stress and strain values are in the deformation initiation region on the long edge of the material and in the top region where the deformation is at the maximum level. As a result of this loading and boundary conditions, the total stress value was determined to be 434.4 MPa. The yield strength of the material (Al 2024 T3) is 524 MPa. In this situation;

Safety Factor = Yield Strength of the Material / Total Stress
Safety Factor = 524 / 434.4
Safety Factor = 1.206 is found.

As a result of the simulation study, it was determined that the hydroforming experimental setup is safe under 110 bar pressure with the specified material and geometries. In the experimental phase of the study, CSG rubber grease was used

to achieve hydraulic pressure. This grease is a calcium soap-based lubricant derived from base oils and is used under conditions not exceeding 70°C. It is typically used for lubrication in low-speed plain bearings under light to moderate loads, as well as in general industrial machinery. The experimental process stages are shown in Figure 3.

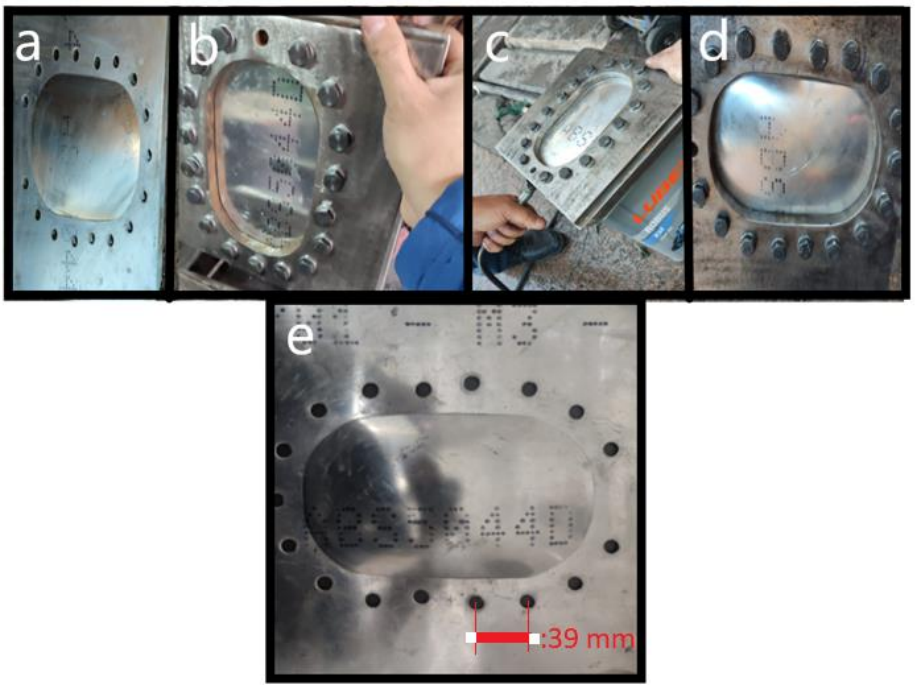


Figure 3. Hydroforming process and product of the rear cargo door hinge housing of the Airbus A321 aircraft. a. Die, b. Mounting of sheet metal into the die, c. Pressurization using a hand pump, d. Sheet metal shaping through the hydroforming process inside the die, e. A321 rear cargo door hinge housing.

The experimental sample was shaped using the hydraulic system pressure provided by the hand pump (Figure 3-c). The shaped area was marked with a marker. Nondestructive Testing (NDT) was performed after the experiment. A High Frequency Eddy Current (HFEC) device was used for crack testing (Figure 4), and thickness measurements were carried out using an Ultrasonic Thickness Measurement device (Figure 5).

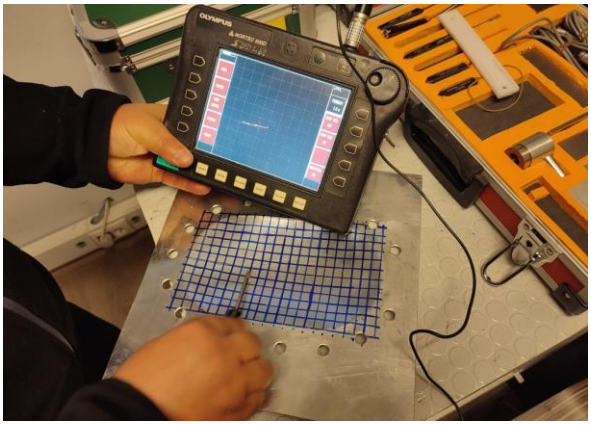


Figure 4. Crack test after Hfec calibration.

As a result of the thickness measurements, it was determined that the thickness value decreased from 1.2 mm to 1.16 mm in the areas where the most significant thinning occurred.

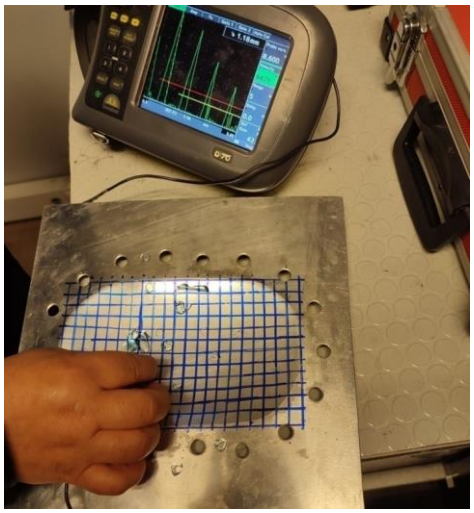


Figure 5. Experimental sample sheet thickness measurement with ultrasonic thickness measurement method.

In this study, shaping of a 1.2 mm thick Al 2024 T3 sheet metal was successfully achieved using hydroforming with grease oil as the fluid medium at a pressure of 110 bar (1600 psi). This pressure was determined to be reliable for the process, leading to an observed maximum cross-section reduction of 0.04 mm. A comparison can be drawn with the work of Pradeep et al. (2022), who utilized a commercial hand pump to apply pressure in increments of 10 bar until failure on Al6063-T6 samples measuring 95 x 95 mm and 0.5 mm thick. Their study involved analyzing the resulting profiles using coordinate measuring machines and profile projectors. They also developed a finite element model (FEM) to assess

deformation, compression depth, and formability across various fluid pressures. It was found that their sample could withstand pressures of up to 170 bar, achieving good formability around 120 bar. The results indicate that hydroforming is a viable method for shaping Al 2024 T3 sheet metal, with specific pressure settings yielding effective results while maintaining the integrity of the component geometry. The close alignment of FEM analyses and experimental outcomes supports the reliability of using simulations for process design and optimization in similar manufacturing applications.

3. Results and Conclusions:

In this study, the design and pressure shaping simulation of the rear cargo door movement cavity of the Airbus A321 aircraft were conducted. Under the determined conditions, an experimental study was performed. In the experimental work, a 1.2 mm thick AL2024 T3 sheet material was used, and shaping was achieved through hydroforming. This enabled a comparison of the obtained results with experimental data. The following results were achieved within the scope of our study:

- It was observed that shaping under 110 bar loading occurred within the desired tolerance range.
- The maximum cross-section reduction was determined to be 0.04 mm.
- The necessary working pressure for hydroforming near the dimensions of 1.2 mm from Al 2024 T3 material was established. This aids researchers and industry professionals in designing processes while considering this pressure range.
- If it is not possible to reach this pressure range for any reason, it was concluded that producing AL2024 T0 material, which has the same alloy but is easier to shape due to not having undergone heat treatment, and can subsequently be hardened through heat treatment, is a viable alternative.
- It was noted that the analysis and simulation work carried out using the FEM method showed a high degree of compatibility with the experimental study. This indicates that simulation is necessary for similar studies prior to mold and system production.

This study highlights the effectiveness of using hydroforming techniques and FEM simulations in the aerospace industry, specifically in the production of the rear cargo door of the Airbus A321. The findings provide valuable insights for future research and practical applications in manufacturing processes, emphasizing the importance of precise pressure settings and material choices.

Conflicts of Interest

The authors declare that there is no conflict of interest regarding the publication of this paper.

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