# Process modelling and die design concepts for forming aircraft sheet parts

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**Abstract**. This study is about typical sheet metal forming processes applied in aerospace industry including flexform, stretch form and stretch draw. Each process is modelled by using finite element method for optimization. Tensile, bulge, forming limit and friction tests of commonly used materials are conducted for defining the hardening curves, yield loci, anisotropic constants, forming limit curves and friction coefficients between die and sheet. Process specific loadings and boundary conditions are applied to each model. The models are then validated by smartly designed experiments that characterize the related forming processes. Lastly, several examples are given in which those models are used to predict the forming defects before physical forming and necessary die design and process parameter changes are applied accordingly for successful forming operations.

## 1.  Introduction

Sheet metal forming represents a major manufacturing effort in the aerospace industry. Typical sheet forming processes applied in aerospace industry include bending, drawing, stretching and flexforming. In all those, it is aimed to convert a flat sheet of metal into a part of desired shape without defects like fracture, excessive thinning or wrinkling. Process simulation, which is conducted by using finite element method, helps to predict the forming defects beforehand. Since there are no physical parts and tools, design and process parameter changes can be easily done leading to fast virtual try-outs. Finally, the right part is obtained the first time reducing material, workmanship and time costs.

In this study, the modelling features of such simulations will be explained and three samples will be shown in which numerical analyses were successfully applied.

## 2.  Modelling Features

The success of the numerical analysis is highly dependent upon proper modeling of material behaviour and friction.

### 2.1.  Material modeling

In order to capture the correct material behaviour, tensile tests (ASTM E8-04), bulge tests (ISO16808) and forming limit diagram tests (ISO 12004-2) of commonly used sheet alloys are conducted. The results are then entered to the simulation for defining the hardening curves, yield loci, anisotropic constants and forming limit curves. Barlat 89 anisotropic yield function and Swift relation are used for the yield surface and hardening curve respectively.

Table 1 shows the obtained material parameters for Aluminum alloy 2024-O.

**Table 1.** Material parameters for AA 2024-O.

| Elastic Modulus [GPa] | Poisson's Ratio | Density [tons/mm$^3$] | Yield Strength [MPa] | Strength Coefficient (K) [MPa] | Hardening Exponent (n) | Lankford Coefficients ($r_0$,$r_{45}$,$r_{90}$) |
|---|---|---|---|---|---|---|
| 69 | 0.33 | 2.8e-9 | 74 | 320 | 0.22 | 0.60, 0.77, 0.60 |

*2.2. Friction modeling*
Friction coefficients for various conditions between the tool and the sheet surfaces are determined by doing dedicated tests and comparing them with numerical conjugates. Table 2 lists some friction coefficient findings [1].

**Table 2.** Friction coefficients for various conditions (tool material: AA 7075, sheet material: AA 2024.

| Condition | Friction Coefficient ( μ) |
|---|---|
| dry | 0.250 |
| oil | 0.125 |
| oil+ nylon film | 0.050 |

## 3. Samples
Three aircraft sheet parts are investigated as: rudder tip, cockpit panel and skin panel. Those parts are from various locations on the aircraft and each has its own forming process and tooling (figure 1).
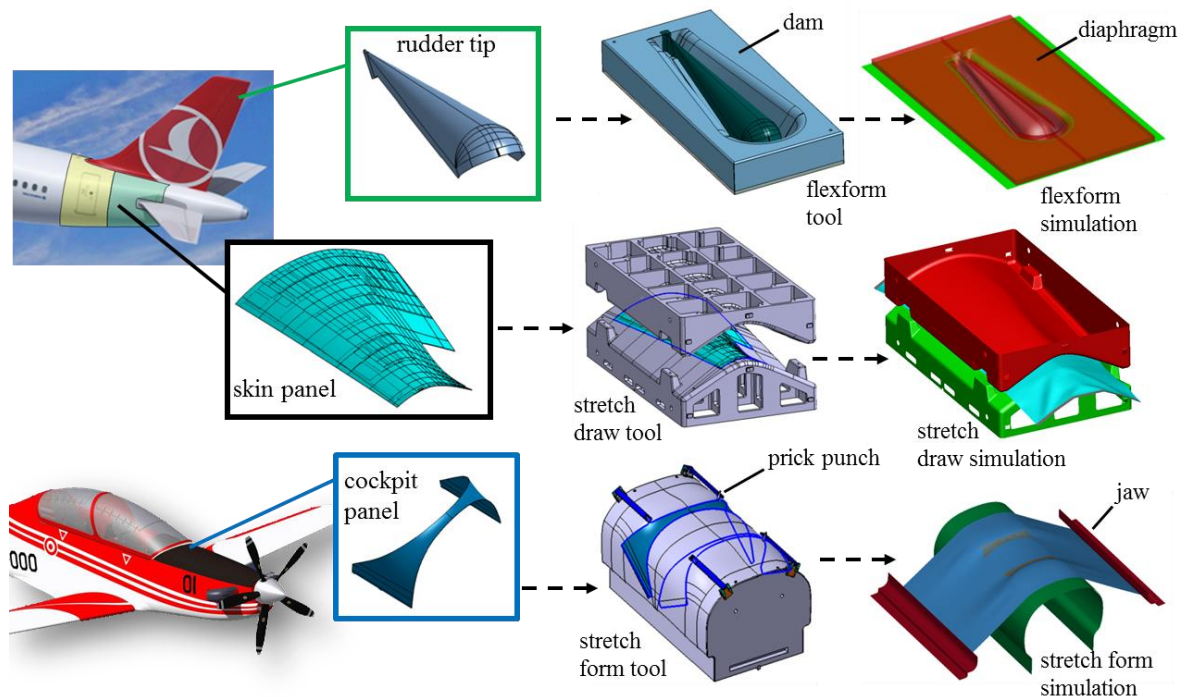


**Figure 1.** Sample parts with locations on aircraft, tools and process simulations.

### 3.1. Rudder tip

Rudder is the part which gives direction to the aircraft and rudder tip encloses the top of the rudder (figure 1). The material is AA 6061 with 1.2 mm thickness. It is rather a deep part which is formed with flexforming process.

*3.1.1. Flexforming process.* In this process, the sheet is formed on a single tool by fluid pressure acting through a rubber diaphragm which takes the place of the counterpart of the tool. For the rudder tip, the tool (material is AA 7075) is a punch type with a dam that prevents wrinkles on the sheet. The flat sheet is attached onto the tool with a guide pin from the tail and with indexing pads from the sides. Some lubricant with nylon film is applied between tool and sheet interface for better sliding. The final part is obtained at about 30 MPa pressure with intermediate steps of stress annealing and trimming.

*3.1.2. Flexforming simulation* [2]. Numerical analysis is performed before physical forming of the rudder tip. The bodies of the model are the die (rigid-shell), the sheet (plastically deformable-shell) and the rubber diaphragm (elastically deformable-solid). The process is half modelled since the part is half symmetric. The boundary conditions are guide pinned node of the sheet, hinged peripheral nodes of the diaphragm and the pressure load on the diaphragm. Explicit time integration scheme is used for solution. Based on the numerical results, forming steps of the real part are determined. Figure 2 shows the thickness distribution of the final part at the half section. The simulation error is 2% when compared with the experiment.
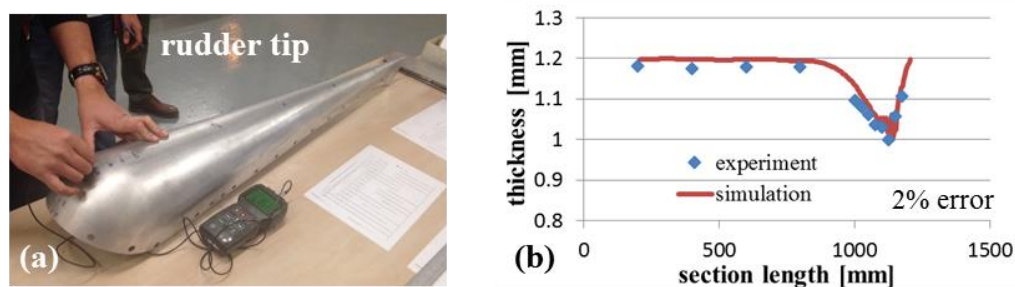


**Figure 2.** (a) Ultrasonic thickness measurement, (b) thickness distribution comparison between experiment and simulation.

### 3.2. Cockpit panel

This part is located on the front cockpit of the aircraft (figure 1). The material is Al 2024 with 1.6 mm thickness. The part has complex contoured surfaces that make it very difficult to stretch.

*3.2.1. Stretch forming process.* In this process, the sheet is stretched over a rigid form-die that acts by hydraulic power while gripped from the sides by jaws which are also hydraulically moved. The form die is attached onto the die table and moves vertically up and down with the die table. For the cockpit panel, the form-die (material is cast iron-GGG45) is designed to produce two parts at once. Some lubricant is applied onto the die for better sliding. Two prick punches are used per part for indexing.

*3.2.2. Stretch forming simulation* [3]. Numerical analysis is conducted to determine the necessary die-jaw movements for successful forming. The process is modelled utilizing quarter symmetry. Form-die and jaw are discretized with rigid shell elements, whereas sheet is with deformable ones. The boundary conditions are vertical displacement of the die, horizontal displacement of the jaw and the constrained nodes of sheet under the jaw. The problem is solved with an explicit scheme. Obtained die-jaw displacement pairs are entered to the NC control unit of the press and the part is formed successfully in a short time. After forming, the part is measured by GOM-Argus® 3-D optical strain measurement system. It can be seen from figure 3 that maximum strain difference between experiment and simulation is about 0.006 which corresponds to 8% of total strain.
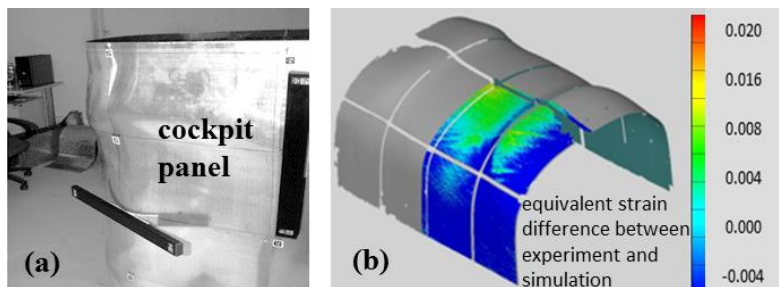
**Figure 3.** Optical strain measurement of cockpit panel and equivalent strain difference between experiment and simulation.

### 3.3. Skin panel

This part is located on the upper side of the tail barrel of the aircraft (figure 1). The material is Al 2024 with 3.2 mm thickness. Negative contours on the part geometry necessitate the usage of stretch drawing process which can be classified as a combination of stretch forming and deep drawing.

*3.3.1. Stretch drawing process.* The sheet is prestretched and wrapped over a lower die by the hydraulic action of flexible jaws; an upper die on the press ram is lowered to complete the required forming. The bosses on the lower die together with the cavities on the upper provide proper closing operation. The skin panel part is stretched for 3% ratio and a ram force of 150 tons.

*3.3.2. Stretch drawing simulation.* The process is checked with numerical analysis. Upper and lower dies are rigidly modelled with shell elements. Sheet is modelled with deformable shell elements except for the regions under flexible jaws (rigidly modelled). The boundary conditions are the movements of upper-lower die (vertically) and the jaws (horizontally). The sheet deviates from the tool surface after unloading (springback). This deviation is measured on real part with laser tracker and the result is compared with simulation. Average error is about 7% (figure 4).
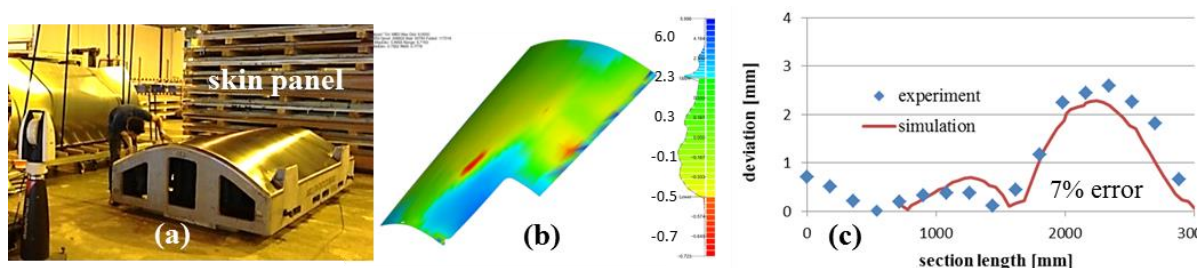


**Figure 4.** (a) Surface deviation measurement of skin panel with laser tracker, (b) measurement result, (c) deviation comparison between experiment and simulation.

## 4. Conclusion

This paper aims to show the application of numerical analysis to aircraft sheet metal forming problems. Three samples were chosen to investigate on flexforming, stretch forming and stretch drawing processes. Results prove that numerical simulation is a successful tool for the prediction of final part.

## References

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