Investigation on Stretch Forming Process of Thick Double-Curved Aluminium Alloy component

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Abstract. Stretch forming process is extensively employed to manufacture aluminium alloys aircraft panel part which possesses large size. These panels usually have a various double curvatures geometric contour. A stretch forming process is proposed to make this part. It indicates that this process which is optimized by research work can be used to manufacture the thick aluminium panel possessing double curved contour with high accuracy. Furtherly in help of the optimization of process parameters by this research work, the manufacturing process may be simplified by means of reducing the forming steps. This stretch forming process has been applied in industry manufacturing. This method is feasible for further stretch process design.

1. Introduction
Aluminium alloy sheets are widely used in aviation industry as material of panel components which usually have large sizes. Stretch forming is one of the most popular process to manufacture these components. Similar to other forming processes, stretch forming is very difficult to precisely form a sheet component possessing double-curved contour because of the elastic recovery of material after unloading, known as the springback effect, especially for the panels with great thickness. Two solutions are used usually to reduce springback, one is optimization of process parameters such as punching force (or closure gap) and stretching distance (tension amount), the other is die compensation method by reshaping the die contour. Finite element method is an effective tool to conduct the optimization of forming process and die compensation with low expense.

There are a lot of research work on stretch forming process. An approach based on the optimal design of flatten blank with pre-machined pockets is proposed for manufacturing the aircraft panel by Song\cite{1}. It is found that the stretching force is crucial parameter to the thickness reduction and the springback\cite{2}. And a systematic numerical simulation on the stretch forming process for an atypical double-curved shape component using multiple die was performed by Park\cite{3}. The stress levels of the alternative stretching paths are compared and the path that produces the least spring-back effect is identified.

As regarding the die compensation methods, the displacement adjustment method has shown its capacity to reduce springback through adjustments to the surfaces of tools in a direction opposite to the direction of the springback\cite{4}. A strategy of the die shape compensation with the consideration of the
undercut criteria is also presented and the automatic surface mapping, projection and manual morphing are implemented[5].

However, fewer researchers have focused on the precision forming for those double curved panels which have large dimensions and important thicknesses. In this study, an optimized double acting stretching forming process is demonstrated for a quite thick aircraft panel component with a large size, which leads to severe springback.

2. Component specification
This presenting component is an aircraft panel with a big dimension about 6000mm×1100mm and the thickness of 6mm. It possesses double curved contour with two apophysis areas (B, C), shown in Figure 1, which result in a requirement of a punch (i.e. upper die) and a multi-step forming process. The original process requires three steps to obtain the parts, between each step the different heat treatment is carried out. This paper proposes a process in a less cost of both economy and time.

The material is the aluminum alloy 2024-O. Tensile tests of three heat treatment states (total annealed, half annealed and original material) are performed. A set of tension tests have been performed to calibrate the material parameters of the blank in Hill'48 model. The obtained material parameters are shown in Table 1.

![Figure 1 schematic diagram the component](image)

| Table 1 Material parameters |
|-----------------------------|
| State | Total annealed | Half annealed | Non-annealed |
| $E$ (MPa) | $6.01 \times 10^3$ | $6.13 \times 10^3$ | $6.17 \times 10^3$ |
| $\nu$ | 0.29 | 0.23 | 0.36 |
| $\sigma_y$ (MPa) | 66.04 | 114.78 | 77.8 |
| $\sigma_t$ (MPa) | 188.59 | 287.86 | 197.54 |
| $r_0$ | 1.66 | 0.59 | 1.16 |
| $r_{45}$ | 1.69 | 0.6 | 1.02 |
| $r_{90}$ | 0.975 | 0.95 | 0.9 |
| Heating condition | 390–410°C 60min | 350–380°C 120min | |
| Cooling condition | 30°C/h Air cooling | - | - |

$E$: Young’s Module, $\nu$: Poisson ratio, $\sigma_y$: Yielding stress, $\sigma_t$: Broke Stress, $r_0$, $r_{45}$, $r_{90}$: Anisotropic parameters

3. Forming process simulation
In this research the stretch-forming procedure consists of three stages, shown in Figure 2:

- Pre-stretching: the metal panel is stretched horizontally to get a certain plastic deformation;
- Punching: the punch moves down and presses the sheet on the die to get the required panel shape,
- Final stretching: the panel is pulled along the clamping direction to increase plastic strain of the sheet in order to reduce springback.
The main reason which leads to the shape error (the deference of contour between the formed component and the die) is springback during unloading and trimming. In this process, the punching force and the stretching amount are the key process parameters which are studied to reduce springback. The punching force controls shape error at beginning and the accuracy of the final product is highly dependent on stretching amount.

Increasing the punching force may reduce the shape error, but the thickness reduction increases correspondingly and sometimes the material occurs instability in the local area. The appropriate punching force can be judged by ‘closure gap’, the distance between the punch and the die. The minimum gap is the thickness of the sheet, if gap is much bigger than thickness of the sheet, it means the panel surface incompletely touch the die and result in shape error. Oppositely the punching force which excess the necessary amount getting the minimum gap might aggravate thickness reduction.

As well the insufficient stretching amount will lead to a significant shapes error owing to the springback because the plastic strain of sheet is not enough, but excessive stretching amount will result in severe thickness reduction, and even fracture. Thus, optimal design of process to choose the suitable punching force and stretching amount is important.

In this study, the tension amounts, the magnitude of sheet deformation which can represent stretching amount, is analysed. An optimal punching force is proposed firstly, and the die compensation is employed as follow.

PAM-STAMP, a commercial FE simulation software with explicit non-linear solver, is occupied to establish our stretching forming model. Regarding the thickness of the blank is 6mm, thick shell element is preferred as it allows the modelling of bending effects. Correspondingly, an elastic-plastic with damage and failure material for 4-node thick shell element material is selected (MAT171), shown in Figure 3.

The implementation of process parameters optimization and die compensation is based on a sequence experiment design and the iterative numerical simulations. In pre-stretching stage, only one parameter analysed is the tension amount. If the tension amount is insufficient, plastic deformation will be too weak on the blank. Thus, 60 mm stretching amount (one percent of component length) is used. In punching stage, several values of punching forces are performed in simulations and its effect on both
thickness and closure gap is investigated. The thickness distribution in state of 150 ton punching force is shown in Figure 4(a). The effect of punching force on both max thinning and closure gap is shown in Figure 4(b).

![Figure 4](image1.png)

(a) thickness distribution at 150 ton punching force   (b) Punching force effect on max thinning and closure gap

Figure 4 Punching force effect on thickness and closure gap

![Figure 5](image2.png)

(a) Thickness distribution at 200mm tension amount    (b) tension amount effect on max thinning and springback

Figure 5 Tension amount effect on the thickness and springback

It indicates that the punching force increment can significantly reduce the closure gap until it reaches 100 ton, which means better shape accuracy. Further increment may induce local defects on the blank surface. On this account, a punching force of 100 ton is proper selection.

In final stretching, 5 tension amounts are tried to balance the thickness distribution and normal springback. The thickness distribution in state of 200mm tension amount is shown in Figure 5(a). The result shows that maximum thinning raises slightly with raising of tension amount and spurts after 175mm, shown in Figure 5(b). In addition, the normal springback descends with increasing of the tension amount until the tension amount reaches 175mm and it becomes a plateau latterly. It reveals that the increasing of tension amount can inhibit the springback effect. Result shows the suitable tension amount in final stretching is 175mm.

4. Die compensation

Since the blank sheet is quite thick (6mm), the springback effect is considerable. As discussed above, the springback is obvious even if the tension amount is up to 175mm. So, a die compensation process is employed using the DIE COMPENSATION module in PAM-STAMP. The die compensation method is widely used to reduce the springback, the principal is to modify the contour of the die according the
feature of the shape error in order to get the correct component shape after springback. It is an iteration process and usually need several trials in help of simulation method or experiment to obtain the appropriate real die contour. The shape error will be reduced gradually until the part shape meets the precision of requirement[6-9]. The procedure of die compensation is as followed:

a) Executing the forming and springback process using simulation method or experiment;
b) Judging if the component shape meets the requirement or not;
c) If “No”, modifying the die contour according the shape error feature;
d) Repeating a), b) and c) until the part meet the demands or reach the iteration time limit.

The software PAM-STAP is used to carry out the process of die compensation. There is diverse die compensation method. In this paper, the maximal distance method is chosen to analysis the component. The distance between a certain node of the designed part and the same node of springback result is main evaluation indicator in this method. And the proportion of nodes who meets the demands is another. In this paper, the distance is 1mm and the proportion must be larger than 95%. The iteration limit time is set to 8. Figure 6 shows the result of each iteration. After 3th iterations, although the maximal springback is about 2.00, the gaps between most node on the final component to the desired one is less than 0.64mm, which meets the demand.

![Figure 6 Component in 3 iterations of compensations](image)

5. Conclusion
In this paper, a research work for optimizing stretching forming process is conducted to obtain a double curved aircraft panel with large dimension as well as important thickness. The two process parameters, punching force and stretching amount, which are the most important influence factors on springback and thinning of sheet, are analysed and optimized using numerical simulation method, and the appropriate values are proposed. Die compensation method is also used to improve the precision of part. As a result, only one stretching forming step is needed to produce qualified parts, instead of original process which need three steps.

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