Determination of Process Parameters in Multi-Stage Hydro-Mechanical Deep Drawing by FE Simulation

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Abstract. In this work, analysis has been carried to simulate manufacturing of a near hemispherical bottom part with large depth by hydro-mechanical deep drawing with an aim to reduce the number of forming steps and to reduce the extent of thinning in the dome region. Inconel 718 has been considered as the material due to its importance in aerospace industry. It is a Ni-based super alloy and it is one of the most widely used of all super alloys primarily due to large-scale applications in aircraft engines. Using Finite Element Method (FEM), numerical simulations have been carried out for multi-stage hydro-mechanical deep drawing by using the same draw ratios and design parameters as in the case of conventional deep drawing in four stages. The results showed that the minimum thickness in the final part can be increased significantly when compared to conventional deep drawing. It has been found that the part could be deep drawn to the desired height (after trimming at the final stage) without any severe wrinkling. Blank holding force (BHF) and peak counter pressure have been found to have a strong influence on thinning in the component. Decreasing the coefficient of friction has marginally increased the minimum thickness in the final component. By increasing the draw ratio and optimizing BHF, counter pressure and die corner radius in the simulations, it has been found that it is possible to draw the final part in three stages. It has been found that thinning can be further reduced by decreasing the initial blank size without any reduction in the final height. This reduced the draw ratio at every stage and optimum combination of BHF and counter pressure have been found for the 3-stage process also.

1. Introduction

Inconel 718 is a Ni-based super alloy and it is one of the most widely used of all super alloys primarily due to large-scale applications in aircraft engines. Inconel 718 comprises 51% of the total weight of the space-shuttle main engine and the alloy is used for more than 1500 individual parts in hydrogen, oxygen and hydrogen-rich steam environments at temperatures ranging from −253 to 760 °C. Inconel 718 derives its high temperature properties from a combination of alloying and strengthening effects, including solid solution strengthening and precipitation hardening [1]. Presently Inconel 718 alloy is being used for manufacturing of cell case (both top and bottom parts) by deep drawing. The cell case bottom dome is deep drawn in four stages to obtain the final shape and dimensions. Some of the problems encountered presently are: thinning on the curved portion (near the bottom) below the acceptable limit, shape profile variation during forming and change in profile during the proof profile test.
In the present work, the possibility of using hydro-mechanical deep drawing (HMDD), in which a counter pressure is applied on the blank during drawing \[2,3\], has been examined to reduce the number of drawing steps. The influence of hydraulic counter pressure on drawability of Inconel alloy was studied and the optimum combination of tool design and process parameters (like draw ratio, maximum pressure, blank holding force etc.) have been suggested with an aim to reduce the number of forming steps and thinning in the part. The tensile properties and formability parameters were determined. These properties were used in the FE simulations of the multi-stage deep drawing of bottom half of the cell case. The thickness distribution and shape profile of the drawn part were studied at each stage. The influence of blank holding force, lubrication (by varying the coefficient of friction) and draw depth on drawability, wrinkling and extent of thinning was studied at each stage.

2. FE simulation of multistage HMDD

2.1 Process details

Presently, the cell case bottom part is deep drawn in 4 stages in conventional drawing process as shown in figure 1. In order to study the effect of counter pressure on thinning and formability of cell case, multistage HMDD (in three stages) of cell case has been simulated by varying draw ratio and tool design parameters at every stage. The various steps of simulation are explained below.

2.2 Modeling of tools

The tools for all the stages i.e. the drawing dies (lower die), the blank holders (upper die) and the punches were modelled using PROE software as surface entity. These models are then imported into the Dynaform as IGES files. In the first stage, the blank of diameter 295 mm was modelled in Dynaform pre-processor (shown in figure 2) and for the subsequent stages, the deformed blank of the previous stage was imported for redrawing in the next stage.

2.3 Material Model

Another important part of simulation using FEM is the selection of appropriate material model. The blank material used is high strength Inconel super alloy. The material is assumed to be rigid- plastic and the power law equation is used as the constitutive equation to account for strain hardening of the sheet during deformation. Barlat’s 3-parameter yield criterion \[4\] is used as it incorporates the effect of both normal and planar anisotropy in the yielding behavior of the material. Material properties such as mass density, Young’s modulus of elasticity, strain hardening exponent, anisotropic

Figure 1. Deep drawing of cell case in four stages with dimensions of the part in each stage.
parameters (R₀, R₄₅ and R₉₀) and strength coefficient (K) etc. are given as input to carry out FE calculations. Barlat’s yield exponent (M) for face centered cubic (FCC) materials is 8.

2.4 Boundary conditions
In the case of HMDD, the counter pressure has to be applied on the surface of the blank. Counter pressure is specified at all nodes on the blank in the opposite direction of the punch travel by applying pressure boundary conditions. There is also provision for applying the counter pressure by element normals. In this case, it is necessary to ensure the normals are oriented downward because the pressure always acts against the element normals. Pressure path (variation of pressure vs. time during deep drawing) that has been used to simulate the process, is an important variable. Pressure path with continuously increasing pressure until the end of the process has been used as shown in figure 3. It was observed that the pressure path with continuous rise until the end of the process has given the better thickness distribution in the cup wall. In the case of the flat bottom cup, friction holding effect between the punch and blank helps prevent the failure of the cup near the punch corner but in the case of hemispherical cup bottom friction holding effect will not be helpful as this portion of the part undergoes stretching and hence higher friction further increases thinning. So, higher pressure at the beginning of the process (at the time when the blank takes the shape of the punch bottom) is not desirable as it can increase the friction holding effect.

2.5 Process parameters
In addition to material properties, process parameters such as coefficient of friction, punch travel, peak counter pressure and blank holding force are very important for accurate simulations. The punch movement is defined in negative Z-direction, which corresponds to the direction of punch axis. The punch velocity is specified using a trapezoidal profile (punch velocity vs. time). This curve is used to define the motion of the punch to a depth that is allowable for a particular draw ratio. To reduce the computational time, an artificial punch velocity of 5000 mm/sec is used in the simulations. Blank holding force (BHF) is applied on the blank by the blank holder in the negative z-direction. Optimum blank holding pressure has been increased with increase in peak counter pressure. The required blank holding force has been calculated using the optimum blank holding pressure and the flange area on which BHF is applied. This method roughly gives the blank holding force and to arrive at the optimum values, the BHF is varied within a certain range in every stage. Process parameters BHF and peak counter pressure are varied in a range and optimum values of these are identified at every stage that will give better thickness (i.e. minimum thinning) in the dome region. In the redrawing stages, the deformed cup in the previous stage is used as the blank material with initial stresses removed to incorporate the effect of annealing in simulations. The friction between the blank and the rigid surfaces is modeled using Coulomb’s law of friction. In hydro-mechanical deep drawing the lubrication can be approximated to semi fluid lubrication because of the influence of fluid under pressure. It causes forced lubrication between blank and die. The coefficient of friction is varied in the range 0.03-0.125 [5].
2.6 Analysis of results in the post processor
Simulations results are analyzed in the post processor to study the drawability, thickness variations in the cup, occurrence of fracture (by superimposing the strain data of the cup on the FLD of the blank material) and wrinkling and the effect of counter pressure on the strain and stress distributions. The result files i.e. stress and strain contour plots and work piece deformation with time are viewed in the post processor.

3. Results and Discussion

3.1 Effect of process parameters
In order to decrease the drawing steps to three it is planned to increase the draw ratio in the first stage since larger draw ratios are not possible in the redrawing stages. So the initial blank of 295 mm diameter is drawn with a higher draw ratio in the first stage. The obtained cup is subsequently drawn in second and third stages to the final dimensions making the total number of drawing steps three.

In stage 1, the initial blank is drawn with a draw ratio of 1.91 using the second stage tooling design of the conventional process except the die corner radius which is increased to 8 mm, as a higher die corner radius ensures smooth flow of material. Peak counter pressure is varied in the range of 20-50 MPa and blank holding force is varied in the range of 300-800 KN. Optimum combination of parameters is identified which gave minimum thinning in the part. Die corner radius of 8 mm has been identified as the optimum value and any further increase in the die corner radius resulted in the body wrinkling because of increase in the unsupported area, though it resulted in better thickness values. Figure 4 shows the thickness variation of the drawn cup at stage 1 with optimum combination of BHF and counter pressure. Slight wrinkling has been observed at the top portion of the cup. Once the periphery of the blank material comes out of the blank holder area, absence of blank holding force results in the above said wrinkling and high die corner radius is also a cause for such a defect. However, as the top portion of the final part is trimmed, this wrinkled part gets removed at the last stage.

Cups drawn with optimum combination of BHF and counter pressure in stage 1 is simulated by drawing with third stage tooling of conventional process. Die corner radius is increased to 10 mm. Higher die corner radius will not increase the unsupported region, so increase in die corner radius contributes to smooth flow of material and will not have a significant influence on body wrinkling. Coefficient of friction between all tools is varied. To ensure the effect of annealing, stresses from all the elements in the first stage are removed. Process variables like peak counter
pressure and blank holding force are varied within a suitable range and optimum values are chosen to get minimum thinning in the drawn part without severe wrinkling as shown in figure 4. Influence of process parameters (peak counter pressure and BHF) on thinning has been analyzed.

The drawn part in FE simulation of the previous stage is drawn to the final shape and size. In this case also, the die corner radius is increased to 10 mm. Coefficient of friction between all tools is taken as 0.1. Effect of annealing is incorporated by removing the stresses from all the elements. Process variables (peak counter pressure and blank holding force) were varied within a suitable range. The influence of process parameters (peak counter pressure and BHF) on the thickness variation in the final part after trimming to the desired height has been observed. Thickness distribution and formability of the drawn cup at stage 3 are shown in figure 5. The minimum thickness in the final component is 0.702 mm which is just above the acceptable limit. The height obtained in stage 1, stage 2 and stage 3 are 120 mm, 158 mm and 196 mm respectively.

![Figure 4](image1.png)

**Figure 4.** Thickness variation in FE simulations of deep drawing of cell case at stage 1 and stage 2.

![Figure 5](image2.png)

**Figure 5.** Thickness variation and formability in the final part after trimming to a height of 160 mm after third stage (μ =0.10).
3.2 Effect of friction coefficient
The FE simulations with best combination of BHF and counter pressure at all the 3 stages are repeated with different values of coefficient of friction. Coefficient of friction between all the tools and the blank was varied between 0.03 and 0.125 at all stages and the simulations were carried out with same process parameters that have been mentioned earlier at each step. Thickness distribution and formability of the drawn cup at stage 3 are shown in figure 6 with coefficient of friction as 0.03. It can be seen from the above results that decreased coefficient of friction value at stage 1 and stage 2 has increased marginally the minimum thickness in the drawn parts. Reduction of friction between tools and the blank improves the thickness distribution which is evident from the results at step 1 and step 2. Friction between the blank and the punch is very important because of profile of the punch. Slightly higher friction is needed for a punch with flat bottom which increases friction holding effect that helps distribute the strains uniformly. In the case with hemispherical punch bottom, the friction between the punch the blank should be minimum.

3.3 FE simulations with reduced blank diameter
Simulations have been carried out using reduced initial blank diameter to reduce the draw ratio in the first stage and hence improve the thickness distribution at every stage. Since in the previous simulations, it has been observed that height drawn at all stages is higher than the actual required height, it has been found that a blank diameter of 275 mm would be sufficient to draw the final part in the 3 stages with required final height after trimming. Since the process parameters have been optimized previously, the same process parameters are chosen in all the three stages. Figure 6 shows the thickness distribution and formability in FE simulations with reduced blank diameter at the final stage with reduced friction (μ = 0.03). The height obtained in stage 1, stage 2 and stage 3 are 103 mm, 138 mm and 182 mm respectively. From this it can be observed that even the reduced blank diameter of 275 mm is sufficient to draw the final component with desired height after leaving sufficient height for trimming.

4. Conclusions
FE simulations have been carried out for multistage hydro-mechanical deep drawing (HMDD) of cell case (bottom part) used for space applications by increasing the draw ratio and modifying the design parameters when compared to conventional multi-stage deep drawing. By increasing the
draw ratio and optimizing BHF, counter pressure and die corner radius in the simulations, it has been found that it is possible to draw the final part in 3 stages and at the same time the minimum required thickness of 0.7 mm can also be achieved in the dome region. The results showed that the minimum thickness in the final part can be increased to more than 0.70 mm from 0.61 mm (in conventional deep drawing). The part can be drawn to the desired height (after trimming at the final stage) without any severe wrinkling. It has been found that thinning can be further reduced by decreasing the initial blank diameter from 295 mm to 275 mm without any reduction in the final height. This reduces draw ratio at every stage and optimum combination of process parameters (BHF and counter pressure) have been found for 3-stage HMDD process.

5. References
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