Multistage forming analysis of spoke resonator end-wall

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Abstract. Spoke resonator components are typically formed by sheet metal forming operations such as deep drawing and bending. End wall, Spoke and Shell are the main components of spoke resonators. A sheet metal blank of niobium material is used to form the End wall and Spoke for a spoke resonator. This paper presents an elasto-plastic finite element analysis for single stage and multi stage forming of spoke resonator End wall. Numerical simulations were performed to investigate the effect of forming process parameters on localized thinning, residual stresses and study of failure such as tearing or wrinkling. Forming tools like die, punch and binder were modeled by UGNX 8.0, a modeling software and finite element analysis of forming has been simulated by Altair HYPERFORM software. The results of the analysis were used to assess the various forming process. The analysis showed that the multistage forming leads to better uniformity in thickness of component. This data will help in selection of appropriate forming process.

1. Introduction
Raja Ramanna Centre for Advanced Technology (RRCAT), Indore is involved in the development of a spallation based neutron research facility for future projects. The facility will consist of a 1GeV high power proton linac, an accumulator ring, spallation target and various beam lines. The neutrons will be generated by bombarding a high power proton beam on heavy atom targets through spallation process. The spallation neutrons will be used for research in the areas of condensed matter physics, materials science, biology, chemistry etc. The 1 GeV proton linac will consist of an ion source and different normal and superconducting Radio Frequency (RF) cavities to accelerate ions to the final energy. These cavities are classified based on β-value ($\beta = v_0/c$), which is defined as the ratio of velocity of particle, $v_0$, to the velocity of light, c. Spoke resonator is a low velocity structure with typical range of $\beta$ varies from 0.1 to 0.6 and used for acceleration of proton and heavy atoms [1]. Physics design of three families of spoke resonator cavities with beta values of 0.11, 0.22 and 0.42 respectively has been carried out by Accelerator & Beam Physics Section, RRCAT. These cavities will accelerate ion beam from 3 MeV to 160 MeV [2]. The cavities will be fabricated using high purity niobium material, which becomes superconducting at very low temperature (~ 9.2 K) [3,4]. After spoke resonators, super conducting elliptical cavities would be employed for beam acceleration up to 1 GeV.
A spoke resonator consists of mainly three components such as End-wall, Spoke and Shell. The end-wall of spoke resonator consists of protruding nose. It is made by either welding two components, nose and outer end wall or stamping/ deep drawing operation from single sheet [5]. The second method is preferable, though it requires use of stamping setup such as die and punch. The sheet metal deep drawing or stamping is a typical seamless forming process to get desired shape of component by plastic deformation. In this process a blank is placed on a die cavity, held in position using a holding plate and pressed against the die cavity using solid punch to get the desired shape. The resonator surface is chemically polished to remove any macroscopic defects developed during forming of component and soft nature of niobium material and then heat treated [6].

Deep drawing is one of the important and widely used metal forming processes to form symmetric and asymmetric components of sheet metals in industries like automobile, packaging etc. Forming operations can be performed in single stage and multiple stages depending upon the complexity of the geometry. From deep drawing, uniform thickness distribution of sheet and highest drawing ratio expected, however residual stresses induced and localized thinning of the component occurs based on contour and shape of die [7]. In multistage forming, rapid increase in drawing force is observed during subsequent stages after first stage forming due to strain hardening [8]. Higher strain hardening coefficient delayed the necking phenomenon so subsequent drawing is possible and formability of the material increases, and springback effect decreases. The multistage forming facilitates the forming of complex and asymmetrical parts, where more than one forming operations are involved. With the advancement of technology, the multi-stage forming has become feasible concurrently with the help of progressive dies. However the multistage forming incurred high cost due to expensive setup. Use of software based on finite element analysis is becoming more important to simulate the multistage forming of metal sheets as well as to design the complex tools for forming. Simulation reduced the time and cost involve in design and development of prototype and helped in optimizing the process parameters [9].

In the present work, finite element analysis of forming processes of spoke resonator endwall performed to see and compare the effect of single stage and multistage forming processes on formability of the material. The various forming tools like die, punch and binder were modeled by UGNX 8.0, modeling software. The finite element (FE) analysis of forming was conducted by Altair HyperForm software [10]. It is a FE based software for incremental sheet metal forming simulation and used for formability analysis. The study of effect of single stage and multistage forming on distribution of thickness and equivalent stress can help to develop the product without expense of material with favorable properties. The efficient and accurate finite element simulation will help in selecting optimal forming process and parameters of tools for manufacturing of spoke resonator endwall with better quality [11].

### 2. Material and modeling

A niobium material is used for forming of spoke resonator components due to favorable properties. Niobium ore processed by electron beam melting and forged into ingots, which is further annealed and rolled into sheets. Annealing under controlled temperature and time is carried out for recrystallization and to obtain the desired grain size [3, 4]. Elasto-plastic material model with mechanical properties of niobium given in Table 1 were used in the present simulation work.

| Table 1. Mechanical properties of Niobium |
|------------------------------------------|
| Modulus of elasticity | 106 GPa |
| Yield strength        | 38 MPa  |
| Ultimate tensile strength | 183 MPa |
| Poisson’s Ratio       | 0.3     |
| Strain Hardening Exponent | 0.38   |
| Density of material   | 8570 Kg/m³ |
A CAD model of spoke resonator end-wall and forming tool for single and multistage analysis has been prepared in UGNX modeling software. The components were meshed in HYPERFORM software. Forming tools like Punch, Die and binder were considered to be rigid and meshed by Rigid R-Mesh and blank was meshed by B-Mesh. Coulomb friction model is used for interacting surfaces. After meshing various inputs like material properties, blank holding force, clearance between die and punch, punch velocity, symmetricity and drawing direction were specified for the analysis as per requirement. Boundary conditions were specified with respect to real process.

The Altair Hyperform, a finite element software was used to solve the model [10]. During multistage forming analysis data file from previous stage imported to next stage for subsequent level analysis. The output of the finite element simulation were analyzed to obtain results of material thickness, percentage thinning, von Mises stresses, and forming limit diagram.

3. Deformation mechanism

Sheet metals are usually processed through cold rolling and their properties differs in rolling and transverse directions. Therefore, the sheet metal forming generally deals with non-linear plastic deformation of anisotropic material [12]. For an isotropic ductile material, von Mises and Tresca's criteria are used, while for anisotropic material Hill's anisotropic criteria is applied. The Hill's criterion is a generalization of von Mises criteria [13] and given by $F \left( \sigma_y - \sigma_x \right)^2 + G \left( \sigma_z - \sigma_x \right)^2 + H \left( \sigma_x - \sigma_y \right)^2 + 2L \tau_{yz}^2 + 2M \tau_{zx}^2 + 2N \tau_{zy}^2 = 2f \left( \sigma_{ij} \right)^2$, where $F, G, H, L, M$ and $N$ are constants. These values determined by anisotropy property of material. The equation will reduce von Mises criteria for isotropic material i.e. $F, G, H = 1$ and $L, M, N = 3$.

In deep drawing of cup, the metal is subjected to three different kinds of deformations. To understand the deformation mechanism of sheet metal forming, an example of deep drawing of a cylindrical cup is shown in figure 1 from [14]. The Figure shows stresses and deformation in pie-shaped segment of circular blank.

![Figure 1. Schematic of stresses and deformation in a section from a drawn cup [14].](image)

During forming operation middle part of the metal sheet comes in contact under the punch tool. It is wrapped around the profile of the punch. The sheet metal in this region is subjected to 2-D stresses (plane) due to the action of the punch result into reduction in thickness. The surrounding part of metal sheet of the blank is drawn radial outward around the punch in the neck region of die. As the punch progressed the outer circumference subjected to compressive strain and tensile strain in tangential and radial direction respectively. The two principal strains leads to thickening of the component as the metal moves inward. When the metal passes over the die shoulder radius during forming, first bending and then straightening occurs. Due to this plastic bending under tension a considerable thinning occurs [14].
4. Results and analysis

4.1. Single stage forming

The figure 2 shows the geometric details of the spoke resonator endwall, which is modeled and simulated under single stage and multi-stage forming. Figure 3 shows the model of the endwall forming tool kinematics. The forming tools consist of blank, binder, punch and die. The initial blank size of 680 mm diameter and 4 mm thickness for endwall, estimated by Radios One Step module in Altair Hyperform. The blank size of 690 mm with machining tolerance of 10 mm has been taken for forming analysis. The die is provided with die shoulder radius of 12 mm and clearance between punch and die is 0.8 mm. These parameters were optimized by finite element analysis. Blank holding force of 10 kN applied by pressure plate or binder to hold the blank during forming.

![Figure 2](image1.png)

**Figure 2.** Geometry of formed component being analyzed

![Figure 3](image2.png)

**Figure 3.** Modeling of Single stage forming Process

A forming limit diagram (FLD), which is the plot of plastic strain history, is used as a tool to establish limits of forming process such as wrinkling, necking and failure during the sheet metal forming process. The forming limit curve (FLC) is plotted by combinations of maximum strain that a component can undergo in various forming operations, without failure [15]. Circular grid method proposed by [16] used...
for determine sheet metal formability. Figure 4 shows forming limit diagram of endwall obtained from simulation under different forming conditions. Red line indicates the fracture limit, yellow line indicates marginal limit and green line indicates limit for wrinkle formation of the formed component. If FLC lies beyond the red line then component gets fractured, whereas if FLC lies between marginal line and green line the component is said to be safe. From the FLD, it has been clearly shown that the component is completely safe during forming.

Figure 4. Forming limit diagram (FLD)

A quarter section of geometry has been picked for the forming analysis because of circular symmetry of the endwall. This saved the simulation time. The thickness analysis of single stage forming of endwall showed that maximum percentage thinning i.e. 9.1% occurred at center nose region of the endwall marked by red contour (Figure 5). The increase in friction coefficient limits the flow of material result into change in thickness. The equivalent stress diagram after forming in single stage is shown in figure 6. The maximum equivalent stress was noted as ~148 MPa in bending region of the sheet around contour. The equivalent stress at the nose section were also high ~135 MPa. However it is smaller than the outer bending zone.

Figure 5. Percentage thinning contour in endwall

Figure 6. Von Mises stress in endwall

4.2. Multi-stage forming

Simulation of multistage forming has been carried out for two-stages and three-stages. In two-stage forming, the component was formed by two sheet metal forming operations namely (a) deep drawing
and (b) bending. In first stage niobium sheet was drawn into conical shape of height 47.80 mm and which is followed by bending in 30 mm radius of flange section in the second stage. The kinematics of the forming steps for two-stage forming process is shown in figure 7.

![Image](image1.png)

**Figure 7.** Stages of the modeling of multistage (two-stages) forming process

In two-stage forming of endwall, it has been observed that the percentage thinning improved and equivalent stress decreases as compared to single stage forming as in single stage the complete blank stretched simultaneously, which causes excessive thinning and stresses in the blank. The thinning percentage contour is presented in figure 8. The maximum percentage thinning was observed in nose region similar to single stage forming process however it was limited to 7.5 %. The maximum equivalent stress is noted as ~78 MPa in outer ring portion which was subjected to bending as has been shown in figure 9.

![Image](image2.png)

**Figure 8.** Percentage thinning contour in 2-stage forming

**Figure 9.** Von Mises stress in 2-stage forming

In three-stage forming a curved profile punch was used for first stage drawn, which enables the maximum amount of material flow into the conical cavity. In the second stage complete deep drawing of component obtained from first stage was done and in the third stage bending of flange part was performed to form the final shape of endwall. After final stage, in three-stage forming, the percentage thinning noted as 6.4% as shown in figure 10, which is better than single stage and two stage results. The improvement in percentage thinning is attributed to use of profile punch during first stage of three-stage forming [17]. Figure shows that the maximum percentage reduction of thickness took place at center part i.e. nose of the endwall. The equivalent stresses were also decreased as compared to the single stage forming and observed as ~93 MPa as shown in figure 11. However there is also middle region where stress are also high ~82 MPa compared to single stage forming. The increase in residual stresses in three stage forming were more compared to two-stage forming and due to strain hardening.
of the niobium material in the previous stages. Hence, it can be concluded that the percentage thinning decreases as the forming conducted in multiple stages and uniformity in thickness increases.

![Figure 10. Percentage thinning contour in 3-stage forming](image1)

![Figure 11. Von Mises stress in 3-stage forming](image2)

5. Conclusion

In this work the finite element analysis of forming operating under single stage and multi stage processes were carried out for spoke resonator endwall. Following points were noted from analysis:

- The comparison of reduction in thickness of contour showed that the maximum thinning i.e. 9.1% occurred at center/nose part of the endwall in single stage forming. While multi-stage forming analysis showed that the percentage thinning improved to 7.5% and 6.4% under two-stage and three-stage forming operation respectively for the same geometry. The improvement in percentage thinning helped in uniformity of thickness of the spoke resonator endwall by employing proper design and selection of forming tool and multistage forming.

- High equivalent stresses were observed in endwall i.e. ~148 MPa in single stage forming. In multistage forming (three-stage) maximum von Mises stress is recorded at edge of flange of magnitude ~93 MPa. This is lower than the stresses induced in single stage forming however more than stresses noted in two-stage forming and due to strain hardening while plastic deformation.

6. References

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