NEAR NET SHAPE FORGING USING THE BACKWARD DEFORMATION METHOD

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Abstract. A new method is presented for the design of preform die shapes in a multistage forging process. The method incorporates a backward linear Lagrange interpolation scheme into the finite element method. In the backward deformation method, the final component shape is taken as the starting point and the die is moved in the reverse direction. The nodal coordinates in the backward direction are interpolated using the linear Lagrange interpolation method, which can specify the location of the nodes in each backward time increment. The method also uses the constant volume concept in conjunction with geometrical features, such as backward die/workpiece overlap attributes, to determine the shape of the perform die.
1 INTRODUCTION

Forging is one of the most economical processes for the manufacture of engineering components. Material cost is an important fraction of the total manufacturing costs so any reduction in material loss during the forging operation has a direct effect on the price of the finished product. With recent improvements in engineering design methods and metal forming technology, flashless or near net shape forging methods have been developed, which result in almost no material wastage during forging. For near net shape forging of complex shapes, one or more intermediate preform stages may be required to achieve the final shape of the product. The optimum design of these perform dies then becomes an important part of the design process. As well as minimizing material wastage, the use of optimum shapes in the intermediate stages can lead to improved quality of the forged component, due to, for example, a reduction in local peak residual stresses in the component, and an extended life of the dies themselves, due to a reduction in the friction energy expended at the die/workpiece interface during forging [1].

In a conventional forging die design process, the designer is required to determine the number of intermediate forging stages as well as the perform shapes. This is normally done by experimental trial and error. However, today, with the support of computer aided design tools, the total manufacturing and tool design costs can be reduced [2]. In addition, in recent years, the application of the finite element method has become a major tool in connection with perform die design e.g. [3].

The backward tracing method was developed by Hwang and Kobayashi [4] to reverse the forming process in a rolling operation in order to design preform rolling passes. Later, this method was used to obtain the preform die shape in the forging of axisymmetric shapes [3, 5]. Park et al. [6] developed a new method based on the backward tracing method and applied it to preform design of a shell nosing. Grandhi et al. [7] introduced the optimum control design algorithm into process parameter design of the forging process. The optimum ram velocity for maintaining the specified strain rate in the billet, for an isothermal disk forging, was generated through this approach. These analyses were all carried out using the finite element method with a rigid viscoplastic material formulation. Design constraints on strain rates and temperature variation are imposed to achieve the desired forging conditions. To date backward forming has been studied in axisymmetric and plane strain cases—the authors are unaware of any three dimensional analyses of the backward forming process.

Biglari et al. [8] proposed a fuzzy-decision making approach, which was developed to specify new boundary conditions for each backward time increment, based on geometrical features and the plastic deformation of the workpiece. In this paper a new approach is developed by incorporating the Lagrange interpolation method [9] within the backward deformation method to determine the backward deformation path of the boundary nodes. This replaces the more computationally intensive iterative procedure used in [6-8]. The method has been incorporated within a non-linear rate dependent finite element framework [10] and results are presented for the case of a plane strain and an axisymmetric forging design.
2 BACKWARD LAGRANGE INTERPOLATION

In figure 1, the use of the linear Lagrange interpolation method is illustrated in the design of intermediate forging die shapes. In the backward simulation, the starting shape is taken as the final die stage (the inverse of the shape of the finished component in flashless forging) and backward geometrical interpolation is conducted in order to reverse the deformation. At the starting point the die and workpiece are in contact and the nodes at the die/workpiece interface are gradually released as the deformation is reversed. The linear Lagrange interpolation between two points can be defined by taking the final shape and the initial billet shape as two extreme points where the interpolation is required and dividing it into \( M \) interpolated coordinate points as shown in figure 1. This can be expressed by

\[
X_d = [0, \Delta X_d, 2\Delta X_d, 3\Delta X_d, \ldots, (N - 1)\Delta X_d]
\]

\[
Y_d = [f(0), f(\Delta X_d), f(2\Delta X_d), \ldots, f((N - 1)\Delta X_d)]
\]

where \( X_d \) and \( Y_d \) are the boundary nodal coordinates of the final shape and \( N \) number of nodes on the die boundary during an iteration and

\[
X_s = [0, \Delta X_s, 2\Delta X_s, 3\Delta X_s, \ldots, (N - 1)\Delta X_s]
\]

\[
Y_s = [g(0), g(\Delta X_s), g(2\Delta X_s), \ldots, g((N - 1)\Delta X_s)]
\]

where \( X_s \) and \( Y_s \) the boundary nodal coordinates of the initial shape (initial billet). During each interpolation step, \( X_d \) and \( Y_d \) will approach \( X_s \) and \( Y_s \) respectively and the whole process of interpolation is conducted in \( M \) iterations as described in the next section.

In addition to defining the path of the boundary nodes, it is also necessary to specify when the die surface comes into contact with the workpiece (or when boundary nodes are released in the backward deformation process). The release of nodes from contact with the die may be controlled by process assumptions, related to the geometry of the component, and other features, such as a need to minimize variations in plastic strain. These issues are discussed further in [8]. In the current work the process assumptions are listed as follows.

1. Since, in forward motion, the nodes between the workpiece/die interface (deep in the die cavities) and die separation line come into contact at the end of forming process, in the backward simulation they should be released at the beginning of backward process.

2. In forward simulation, the workpiece nodes near the line of symmetry normally come into contact with the die at the start of forming, therefore in the backward simulation they should be released from the die surface at the end of the backward interpolation.

3. Volume consistency during all backward interpolation increments must be ensured.
The implication of point 3 above is that throughout the backward deformation the volume of the deforming billet remains constant and equal to the final component volume. (Note that this ignores the effect of elastic deformation during the deformation process, which is expected to be negligible.)

2.1 Interpolation Process Boundary Conditions

The process boundary condition is specified at the start and end of the process. In order to determine the intermediate nodal coordinates, the linear Lagrange interpolation approach is used. Therefore, in step \( k \)

\[
\begin{align*}
\text{if } k &= 0 \text{ then } \\
X_k &= X_d \\
Y_k &= Y_d
\end{align*}
\]

(5)

\[
\begin{align*}
\text{if } k &= M \text{ then } \\
X_k &= X_s \\
Y_k &= Y_s
\end{align*}
\]

(6)

where \( k = 0 \) and \( k = M \) mean beginning of step 1 and the end step \( M \) respectively. \( X_s \) and \( Y_s \) are the nodal coordinates selected on the boundary of the billet and \( X_d \) and \( Y_d \) are the nodal coordinates specified at the die surface. Note that the distance between neighbouring nodes on the die and billet boundaries is equal at the beginning of the interpolation process (\( \Delta X_s = X_d \)). For an intermediate stage, the \( X \) coordinate is given by,

\[
X_k = X_d \left( 1 - \frac{k}{M} \right) + X_s \left( \frac{k}{M} \right)
\]

(7)

and the \( Y \) coordinate by,

\[
Y_k = Y_d \left( 1 - \frac{k}{M} \right) + Y_s \left( \frac{k}{M} \right)
\]

(8)

The volume consistency condition is then enforced at each backward interpolation step, such that the volume of the final shape is equal to the volume of the workpiece. The specification of this condition is discussed in section 4 and 5, as it depends on the geometry of the forging (whether plane strain or axisymmetric).

3 MATERIAL PROPERTIES AND CONSTITUTIVE MODEL

The workpiece is a low carbon steel with yield stress of 700 MPa and Young’s modulus of 200 GPa. The constitutive model used accommodates rate dependent deformation with von Mises yield criteria and isotropic hardening. The plastic strain rate is expressed as:

\[
\dot{\varepsilon}^{pl}_{ij} = \frac{3}{2} \dot{\varepsilon}^{pl} \frac{s_{ij}}{\bar{\sigma}}
\]

(9)
where $S_{ij}$ is the deviatoric part of the stress tensor, $\sigma$ is the equivalent (von mises) stress, and $\dot{\varepsilon}^{pl}$ is the equivalent plastic strain rate, defined by the flow rule:

$$\dot{\varepsilon}^{pl} = D \left( \frac{\sigma}{\sigma_0} - 1 \right)^n$$

(10)

where $D$ and $n$ are material parameters and $\sigma_0$ is the yield stress. The material parameters in this simulation were chosen as $D = 40/s$ and $n = 5$.

The above material formulation is for small deformation theory. For a large deformation analysis as is used in this case, the equivalent plastic strain rate $\dot{\varepsilon}^{pl}$ is replaced by the symmetric part of the rate deformation tensor, $L^p$, where

$$L^p = \dot{F}^{pl} (F^{pl})^{-1}$$

(11)

where $F^{pl}$ is the plastic part of deformation gradient, $F$. [10].

### 4 PLANE STRAIN CASE

In a plane strain case the volume consistency in each interpolated step can be achieved by satisfying the area consistency condition. The area can be calculated using Simpson’s discrete integration rule as follows:

$$S = \sum_{i=1}^{N} f(X_i + \Delta X_i) \times \Delta X_i$$

(12)

Before the application of the volume consistency condition the area of each intermediate shape, determined from the Lagrange interpolation, is different from the final shape. Therefore a volume/area correction factor $C$ is defined as

$$C = \frac{S_d}{S_k}$$

(13)

where $S_k$ is the interpolated shape area and $S_d$ is the final shape area. To obtain the corrected coordinates of the intermediate shapes the volume/area correction factor is used as follows:

$$X_k(\text{Modified}) = C \times X_k$$

(14)

$$Y_k(\text{Modified}) = C \times Y_k$$

(15)

Figures 2 and 3 show the forward and backward simulations respectively, using the finite element method, of a forging process under plane strain conditions. Due to symmetry only half of the forging geometry is modelled. In Figure 3, the starting shape is the final component shape and ending shape is a square billet. Figure 4 illustrates the two stage forging process using two sets of preform and finishing dies. The comparison of accumulated plastic
strain for the forging simulation shown in figure 2 and figure 4 is illustrated in figure 5. As can be seen here a more uniform plastic strain has been achieved using the proposed intermediate preform shape.

5 AXISYMMETRIC CASE

In the axisymmetric case, the area is again calculated using Simpson’s rule as follows:

\[ S_i = f(r_i + \Delta r_i) \times \Delta r_i \]  

and the volume is

\[ V = \sum_{i=1}^{N} S_i \times 2\pi r_i \]

where \( r_i \) is the radius for any \( S_i \) in cylindrical coordinate. The volume correction factors for interpolated shapes are thus obtained from

\[ C = \left( \frac{V_d}{V_k} \right)^{\frac{1}{3}} \]

where \( V_k \) is the volume of the interpolated shape and \( V_d \) is the final shape volume. The corrected coordinates of the intermediate shapes are then obtained from equations (14) and (15).

Figures 6 and 7 show forward and backward simulations, respectively, of the forging process for an axisymmetric analysis. Figure 8 illustrates the analysis of a two stage axisymmetric forging using two sets of preform and finishing dies. The comparison of accumulated plastic strain for the forging simulations shown in figures 6 and 8 is illustrated in figure 9. It is clear that more uniform plastic strain has been achieved using the proposed axisymmetric preform shape.

6 CONCLUSIONS

A new method has been presented for the design of preform shapes for multistage forging. The linear Lagrange interpolation method, in conjunction with the finite element method, has been used to determine the nodal coordinates that form the boundary shape of intermediate shapes in the backward simulation method. A number of simulations were conducted to select the shape of the workpiece at each Lagrange backward process. The resultant boundary shape can then be used as the preform die in a forward simulation analysis. Examples of the forging for plain strain and axisymmetric workpieces were studied. More uniform plastic strain was reported through the use of this method for complex geometries compared to single stage forming.

REFERENCES

[1] G.B. Yu and T.A. Dean, A practical computer-aided approach to mould design for


Figure 1: Intermediate perform shape design based on linear Lagrange interpolation.
Figure 2: Forward FE simulation of one stage forging (plane strain case).
Figure 3: Backward simulation of forging process using linear Lagrange interpolation (plane strain case).
Figure 4: Forward FE simulation of two stage forging (plane strain case).
Figure 5: Plane strain analysis of a forging operation (a) Accumulated plastic strain in one stage forging, (b) First stage of forging for a two stage operation, (c) Second stage of forging.
Figure 6: Forward FE simulation of one stage forging (Axisymmetric case).

Figure 7: Backward simulation of forging process using linear Lagrange interpolation (Axisymmetric case).
Figure 8: Forward FE simulation of two stage forging (Axisymmetric case).
Figure 9: Axisymmetric analysis of a forging operation (a) Accumulated plastic strain in one stage forging, (b) First stage of forging for a two stage operation  (c) Second stage of forging  (Axisymmetric case).