A viscoplastic Pseudo Inverse Approach for Optimal Tool Design in Forging Process

Anoop Ebey THOMAS[1,2,a], Ali HALOUANI[1], Yu Ming LI[1], Fazilay ABBES[1], Boussad ABBES[1], Ying Qiao GUO[1] and Jean Louis DUVAL[2]

[1]*GRESPI/MPSE, Université de Reims Champagne Ardenne, Reims, France*
[2]*ESI Group, 99 Rue des Solets, 94513 Rungis, France*

Abstract. The deformation of a metallic workpiece in hot or warm forging conditions can be considered as rate dependent. The Pseudo Inverse Approach developed for cold forging considering elastoplasticity is extended to include the effects of strain rate dependent viscoplasticity. This method is coupled with an optimization procedure to obtain the optimal part tool shape for a metal forging process. The equivalent plastic strain variation in the final part and the maximal punch force during the forming process are taken as multi-objective functions. The tool shapes are represented by B-Spline curves. The vertical positions of the control points of B-Spline are taken as design variables to obtain optimal shape of the preform in a multi-step process

1 Introduction

Forging is one of the oldest metal forming process in which a billet is plastically deformed to form a desired shape and improve the material properties. Most forging operations are quite complex and require two or more stages [1]. Thus to increase the quality and the efficiency of production, it is necessary to have an optimal preform.

Most numerical simulations of the forging process rely on classical incremental methods [2]. Though they provide good strain and stress estimations the computation time is very high and unsuitable for optimization algorithms. In this context, there is a need for a fast and robust forging solver for the preform design and optimization.

The main objective of the present work is to simulate and optimize a two-stage metal forging process considering the rate dependent behaviour of metals to obtain an optimal preform shape. The numerical results obtained using the PIA is compared to that obtained by classical incremental approach.

2 Pseudo Inverse Approach

In contrast to classical incremental approaches, the inverse approach exploits the known shape of the final part and executes the calculation from the final part to the initial billet. In the Inverse Approach (IA), this is done in a single step whereas in the PIA [3] intermediate steps are introduced to improve the stress estimation by considering the deformation history. The main steps of the PIA can be summarized as follows:

- Using the known shapes of the initial billet and the desired final part, intermediate shapes are generated geometrically
- The geometrically generated intermediate shapes are corrected by a free surface method to obtain kinematically admissible intermediate configurations satisfying the equilibrium conditions.
- An inverse calculation is carried out between two successive steps starting from the initial shape to obtain the stress and strain fields at each step.
- A special transfer of stress and strain is carried out between the two independent meshes and is used for the plastic integration in the subsequent step.

3 Viscoplasticity Equations

Using an additive decomposition of the total strain rate into an elastic part and viscoplastic part, similar to the Prandtl-Reuss equations in the case of inviscid plasticity we have,

$$\dot{\boldsymbol{\varepsilon}} = \dot{\boldsymbol{\varepsilon}}_{\mathrm{e}} + \dot{\boldsymbol{\varepsilon}}_{\mathrm{vp}} \tag{1}$$

$$\dot{\boldsymbol{\sigma}} = [\mathbf{H}^e]\dot{\boldsymbol{\varepsilon}}_{\mathrm{e}} = [\mathbf{H}^e](\dot{\boldsymbol{\varepsilon}} - \dot{\boldsymbol{\varepsilon}}_{\mathrm{vp}}) \tag{2}$$

Strain rate-dependent plasticity models can be classified into two main categories, namely the overstress models and the consistency model. The overstress models (Perzyna model [4], Duvaut-Lions model [5], etc.) allow the stress state to be outside the yield surface and directly

[a] Corresponding author: anoop-ebey.thomas@etudiant.univ-reims.fr

define the plastic relaxation equations in the stress space. Consistency models first proposed by Wang [6] and used by others obtain the viscoplastic regularization by introducing a rate-dependent yield surface. The yield function can expand and shrink not only by hardening or softening effects, but also by hardening rate or softening rate effects. The standard Kuhn-Tucker conditions also apply in the consistency model.

In the consistency model, the yield function for a rate-dependent material considering isotropic constitutive law and Von Mises plasticity can be written as,

$$f\left(\boldsymbol{\sigma}, \bar{\varepsilon}_{vp}, \dot{\bar{\varepsilon}}_{vp}\right) = \sigma_{eq} - \sigma_Y\left(\bar{\varepsilon}_{vp}, \dot{\bar{\varepsilon}}_{vp}\right) = 0 \qquad (3)$$

where,

$$\sigma_{eq} = (\boldsymbol{\sigma}^{\mathbf{T}}\mathbf{P}\boldsymbol{\sigma})^{1/2} \qquad (4)$$

σ_{eq} is the equivalent stress $\sigma_Y\left(\bar{\varepsilon}_{vp}, \dot{\bar{\varepsilon}}_{vp}\right)$ is the flow stress corresponding to the accumulated viscoplastic strain $\bar{\varepsilon}_{vp}$ and the viscoplastic strain rate $\dot{\bar{\varepsilon}}_{vp}$.

Similar to the case of inviscid plasticity, the viscoplastic strain rate can be defined as,

$$\dot{\bar{\varepsilon}}_{vp} = \dot{\lambda}\frac{\partial f}{\partial \boldsymbol{\sigma}} \qquad (5)$$

where $\dot{\lambda}$ is the plastic multiplier rate and can be determined by the consistency condition of the yield surface and using an implicit scheme the stress field at the next step can be found as

$$\boldsymbol{\sigma}_{n+1} = \boldsymbol{\sigma}_n + [\mathbf{H}^e](\Delta\boldsymbol{\varepsilon} - \frac{\Delta\lambda}{\sigma_{eq,n+1}}[\mathbf{P}]\boldsymbol{\sigma}_{n+1}$$
$$= \left([\boldsymbol{I}] + \frac{\Delta\lambda}{\sigma_{eq,n+1}}[\mathbf{H}^e][\mathbf{P}]\right)^{-\mathbf{1}}(\boldsymbol{\sigma}_n + [\mathbf{H}^e]\Delta\boldsymbol{\varepsilon}) \qquad (6)$$

It should be noted that these equations are completely equivalent to the equations in the case of inviscid plasticity [3] and are on account of the fact that the flow function is defined by the rate-dependent yield surface.

4 Solution Schemes

4.1 Return Mapping Algorithm

The Return Mapping Algorithm [7] based on the Newton method is the most widely used scheme for the plastic integration of constitutive equations. This algorithm is computationally expensive due to the iterative process and as is usual for Newton-Raphson iterative schemes, can lead to convergence issues in the case of large increments if a suitable initial value is not defined.

4.2 Direct Scalar Algorithm

The Direct Scalar Algorithm [8] proposes a direct scheme for evaluating the plastic integration rate by using the notion of the equivalent stresses. By changing the constitutive equations in terms of unknown stress vectors into scalar equations in terms of equivalent stresses, which can be directly obtained using the tensile curves / plasticity models, we can directly calculate $\Delta\boldsymbol{\lambda}$ without the need for an iterative solution [3].

5 Viscoplasticity Model

Numerous empirical and semi-empirical models are available for computational viscoplasticity. The empirical model proposed by Johnson and Cook [9] is the most popular among them and is used in this study although the formulation can be valid for any hardening rule of the form $\sigma_Y\left(\bar{\varepsilon}_{vp}, \dot{\bar{\varepsilon}}_{vp}\right)$.

The Johnson-Cook relations, without considering the thermal effects, can be stated as,

$$\sigma_Y = \begin{cases} \left[A + B\left(\bar{\varepsilon}_{vp}\right)^n\right]\left[1 + C\log\left(\frac{\dot{\bar{\varepsilon}}_{vp}}{\dot{\bar{\varepsilon}}_0}\right)\right] & if\ \dot{\bar{\varepsilon}}_{vp} \geq \dot{\bar{\varepsilon}}_0 \\ \left[A + B\left(\bar{\varepsilon}_{vp}\right)^n\right] & if\ \dot{\bar{\varepsilon}}_{vp} < \dot{\bar{\varepsilon}}_0 \end{cases} \qquad (7)$$

This leads to a discontinuity in the hardening relation and has to be kept in mind when using the iterative methods for the solution process to guarantee convergence.

6 Numerical Results

The results of the simulation obtained by PIA is compared with those obtained by the incremental approach of the ABAQUS®/Explicit code. The billet section is meshed with 899 nodes and 1674 axisymmetric triangle elements.

The billet material considered is ARMCO Iron having the following properties: Young's modulus E = 207 GPa, Poisson's ratio ν = 0.3, Johnson-Cook model parameters, A = 175 MPa, B = 380 MPa, n = 0.32, C = 0.06.

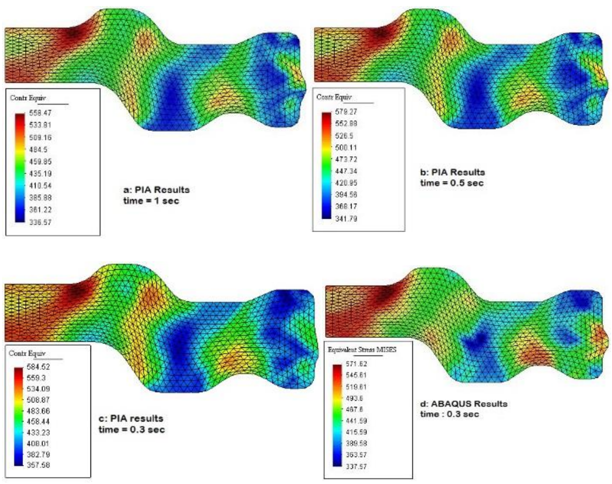

Figure 1. Comparison between PIA and ABAQUS®.

7 Optimization

The main aim of the optimization problem is to find the best preform shapes in the design space relative to the different optimization criteria. In this study the PIA is taken as the forging solver and is combined with an NSGA-II algorithm to minimize the objective functions. Usually a multi-objective optimization process requires a large number of forging simulations and is very time consuming. A surrogate meta-model can provide global approximations of the multi-objective functions [10] and in this study a Kriging method is used to obtain the surrogate meta-model. The objective functions and constraints is the same as the ones used in [11]. They can be stated as follows.

$$F_{obj}^{I} = min\left(\frac{1}{V_t}\sum_{i=1}^{N_{elt}} V_i\left(\bar{\varepsilon}_{vp}{}^{i} - \bar{\varepsilon}_{vp}{}^{avg}\right)^2\right) \quad (8)$$

where,

$$\bar{\varepsilon}_{vp}{}^{avg} = \frac{1}{V_t}\sum_{i=1}^{N_{elt}} V_i\,\bar{\varepsilon}_{vp}{}^{i}$$

$$F_{obj}^{II} = \min(F_{max}) \quad (9)$$

$$\frac{V_{initial} - V_{actual}}{V_{initial}} \leq \varphi \quad (10)$$

The shape of the starting preform is determined by the proportional method and then modified in the optimization loop to satisfy the objective functions. The control point so the parametric B-Spline curves can be active or passive as shown in Fig 2. Only the vertical displacements are taken as geometrical parameters to reduce the number of design variables.

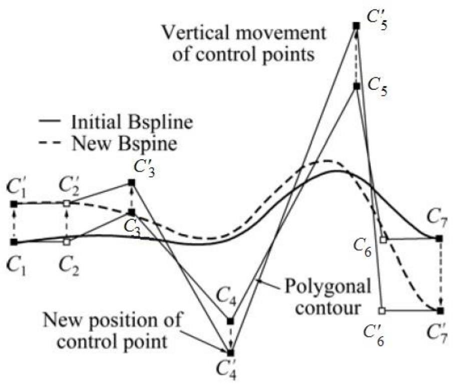

Figure 1. B-Spline curves defining the preform shape.

8 Conclusions

The Pseudo Inverse Approach developed for multi-stag cold forging applications can be extended to hot and warm forging modelling based upon the viscoplastic models. The distributions of the equivalent plastic strain and the Von Mises stress of the solution obtained by PIA are quantitatively very similar to the ones obtained by ABAQUS®. This fast and robust solution method can be used as a good tool for the optimization of the preliminary preform design and other parameters of the forging process. In the future a coupled thermo-mechanical model will be developed in PIA to simulate the complete hot forging process. An extension of the model to complete 3D cases is also envisaged.

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