A Simulation of Hollow and Solid Products in Multi-Pass Hot Radial Forging Using 3D-FEM Method

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ABSTRACT: Radial forging is an incremental forming process, where the total deformation is achieved by successive individual forming steps. Most researchers investigating radial forging processes have used axisymmetric models. In this research, multi-pass hot radial forging of short hollow and solid products are investigated using a 3-D finite element simulation. The workpiece is modeled as an elastic-viscoplastic material. Three-pass radial forging of solid cylinders and tube products are simulated. Temperature, stress, strain, and metal flow distributions are obtained in each pass through a 3D thermo-mechanical simulation. Finally, the results of 3D FEM models are compared with results obtained by axisymmetric FEM models from previous work and with available experimental data.

Key words: Radial forging, solid forging, mandrel forging, 3-D FEM.

1 INTRODUCTION

Radial forging is a hot or cold forging process utilizing two or more radially moving anvils, or hammer dies, to produce solid or tubular components with varying cross section along their length [1]. Radial forging is a cost-effective and material-saving forming process for reducing the round, square and rectangle cross-sections of rods, tubes, and shafts. This process may be performed cold or hot on metals such as steel alloys, titanium alloys, beryllium, tungsten, and high-temperature super-alloys. The properties of products of radial forging include tight tolerances, smooth surface finish, preferred fiber structure, minimum notch effect, and homogenous grains due to full penetration of deformation to the core of the workpiece [2]. The process properties include low energy consumption, considerable material savings, avoiding surface cracks, center bursts, and suck-in at the ends of work piece, and short process cycle times [3]. Radial forging was first developed in Austria in 1946. It was initially used for hot forging of small parts and cold forging of tubes over mandrels [4]. Radial forging is now widely used for reducing the diameter of ingots and bars, forging of stepped shafts and axles, and for producing tubular components with and without internal profiles. The process possesses the capability for virtually chip-less manufacturing of rods and tubes to provide precision-finished products. Figure 1 shows the principle of radial forging of rods with a four-hammer radial forging machine. Lahoti et al. [5-6] analyzed the mechanics of radial forging process, RFP, for single and compound angle dies using the slab method. Tzaeng and Kobayashi were the first to model tube forging using finite element method [7]. However their work was based on an isothermal analysis and they assumed that the bore diameter of preform was equal to the mandrel diameter. The visco-plastic finite element model, which accounts for the effect of rate-dependent materials, was found suitable for modeling hot metal-forming processes like hot radial forging. In this study the workpiece is modeled as an elastic-viscoplastic material. A mixture of coulomb law and constant limit shear is applied to simulate the workpiece-mandrel and workpiece-die contact. Three-pass hot radial forging of solid cylinders and tube products are simulated.

Temperature, stress, strain, and metal flow distributions are obtained in each pass through a 3D thermo-mechanical simulation. Finally, the results of 3D FEM models are compared with results obtained by axisymmetric FEM model of previous work and with available experimental data.

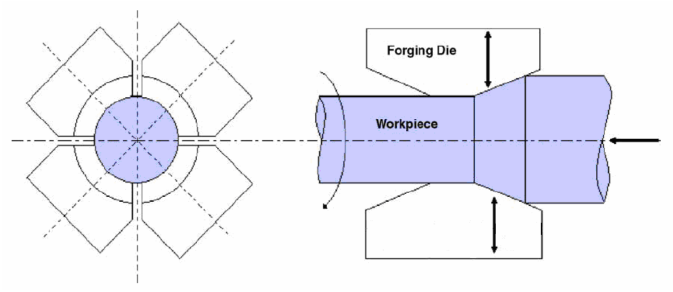


Fig1. The principle of radial forging machines [4].

2 FEM MODELING

The radial forging process is characterized by complex cyclic and transient loading conditions. Thus, the FEM model should have the capability to analyze complex deformation and heat transfer for the determination of material flow and deformations. In this study some process parameters such as rotational feed, axial feed, length of stroke and die geometry are considered. The commercial finite element software ABAQUS is used to model the RFP and to determine the thermal effects on deformation of the products. Finite element model for the tube product is shown in figure 2.

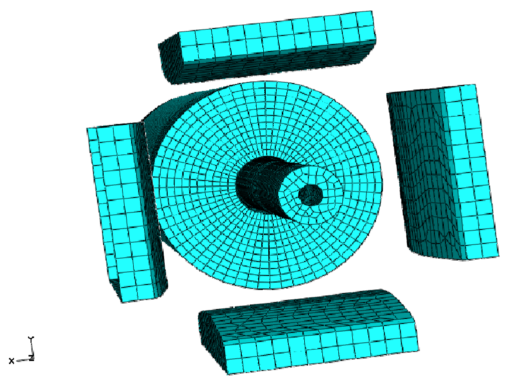


Fig2. FEM Model, hollow Cylinder Forging.

To model the friction in the contact surfaces, a mixing of coulomb law and constant limit shear in which the limiting shear stress is obtained by $m\bar{\sigma}/\sqrt{3}$ was used. In this model $\bar{\sigma}$ is the flow stress and m is the friction coefficient. Analysis of deformation process depends on many factors such as initial shape of material and dies, rate of deformation, temperature, constitutive equation, friction and so on. In this study to obtain accurate flow stress data for FEM simulations the behaviour of material was determined using the dilatometery test which is one type of hot compression test [8]. The dilatometery tests were performed according to AISI 4337 at four different temperatures of 850, 950, 1050, 1100°C. The least square curve fitting on the dilatometery experimental data for material was performed using table-curve-3D software that shows the results were best fitted under Inouye equation of the form:

$$\sigma = A\varepsilon^n\dot{\varepsilon}^m \qquad (1)$$

The magnitude of the constants A, m and n are given in table 1.

Table1. Elastic-viscoplastic properties of material.

Temperature	850	950	1050	1100
A (Pa)	2.63e8	1.54e8	1.36e8	1.095e8
n	0.102	0.115	0.116	0.079
m	0.071	0.134	0.108	0.131

Transient heat transfer occurs by radiation, free convection and conduction during deformation in each pass. Also, in hollow forging there is conduction between mandrel and workpiece since mandrel is colder than the workpiece. Two sets of springs in chuck heads, which allow limited movement of workpiece in the axial direction during forging, are considered. Radial velocity of each die was considered to follow that of harmonic or sinusoidal function like a slider crank mechanism. In simulations thermal and mechanical properties of a low alloy steel are used. This process has three passes with each pass having 50 strokes. The dimensions of the workpiece, hammer and mandrel which are used in modeling are given in Table 2.

Table 2. Geometry of workpiece, hammer and mandrel.

Length of workpiece	1.6 m
Outer diameter of perform for solid and hollow	0.54 m
Inner diameter of perform for hollow	0.15 m
Outer diameter of product for solid and hollow	0.39 m
Inner diameter of product for hollow	0.13 m
Outer diameter of mandrel	0.13 m
Die land length	0.13 m
1st die inlet angle	6°
2nd die inlet angle	8°
Total length of die	0.68 m
Maximum velocity for die per stroke	400 mm/s
Axial feed per stroke	0.02 m
Rotational feed per stroke	12°

3 RESULTS

In this section the results of this investigation will be presented. It should be noted that only the important results will be discussed due to space limitation. The maximum effective plastic strain of hallow and solid forged products at the end of each pass are shown in figure 3.

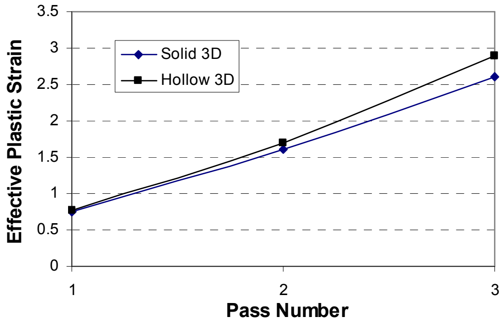
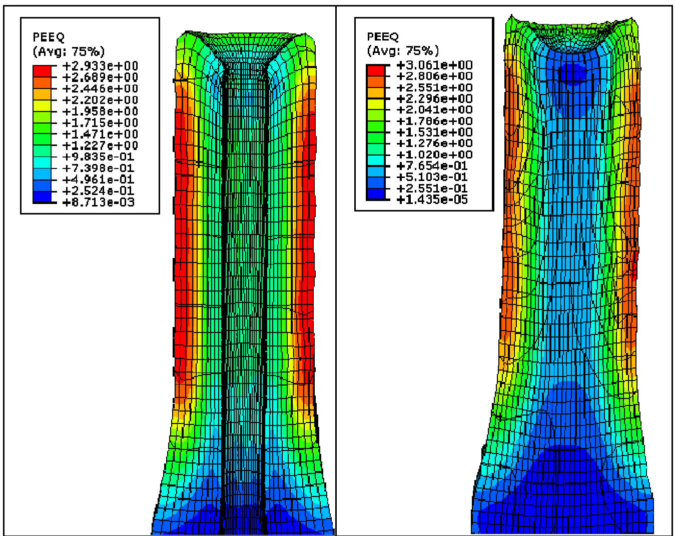


Fig3. Maximum effective plastic strain of products at the end of each pass.

As can be seen in this figure the maximum effective plastic strain increases by increasing the number of passes. Figure 4 shows the effective plastic strain distribution after the third pass. According to this figure the tube product has a more uniform strain distribution compared to the solid cylinder. These results can be verified experimentally by cutting some samples along the workpiece and macro etching them. Figure 5 shows the results of such experimental observations. Flow pattern in the hollow and the solid cylinder products after macro etching can be seen in this figure [3]. The compacted flow pattern in figure 5b indicates the penetration of material deformation through out the tube product thickness.



Hollow cylinder | Solid cylinder

Fig4. Effective plastic strain distribution of products after third Pass.

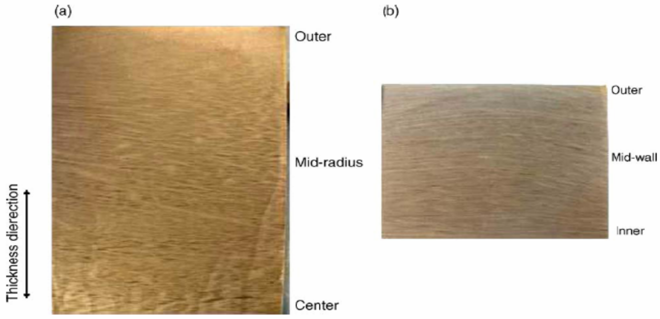


Fig5. The flow pattern of tube and cylinder forged product. a) Solid Cylinder, b) Hollow Cylinder.

Figures 4 and 5 show that the maximum deformation of the tube occurs at the inner and outer surfaces. Figure 6 shows the comparison between the results obtained from axisymmetric and 3D FEM simulations. As can be observed in this figure the trend of both results is similar and indicates an increase in the maximum equivalent plastic strain by increasing the number of passes.

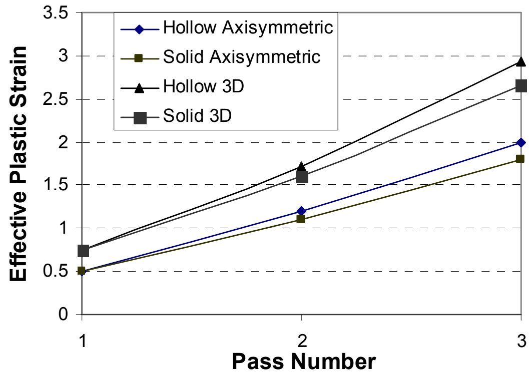


Fig6. Comparison of the maximum equivalent plastic strain through axisymmetric and 3D FEM simulations.

Temperature distribution is as important as strain distribution in the final product properties. Temperature distributions in the solid and tube products after each pass are shown in figure 7.

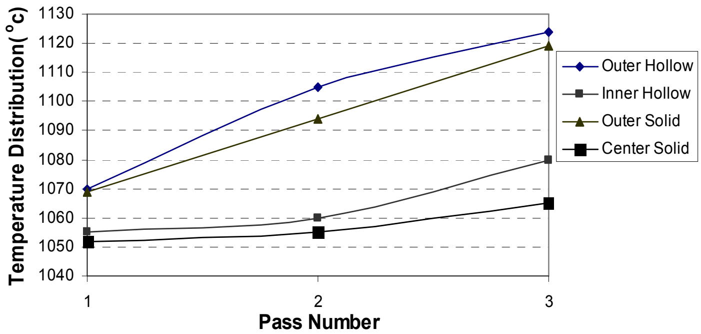


Fig7. Temperature distribution of products after each pass.

In order to manufacture products with improved properties, the temperature gradient should be as low as possible. As shown in this figure temperature gradient in the cylinder is higher than in the tube due to lower heat transfer in the solid cylinder. This temperature gradient leads to a non-uniform microstructure.

Figure 8 shows the temperature distributions in the products from the axisymmetric models. Through thickness temperature gradients can be observed in the products at higher number of passes.

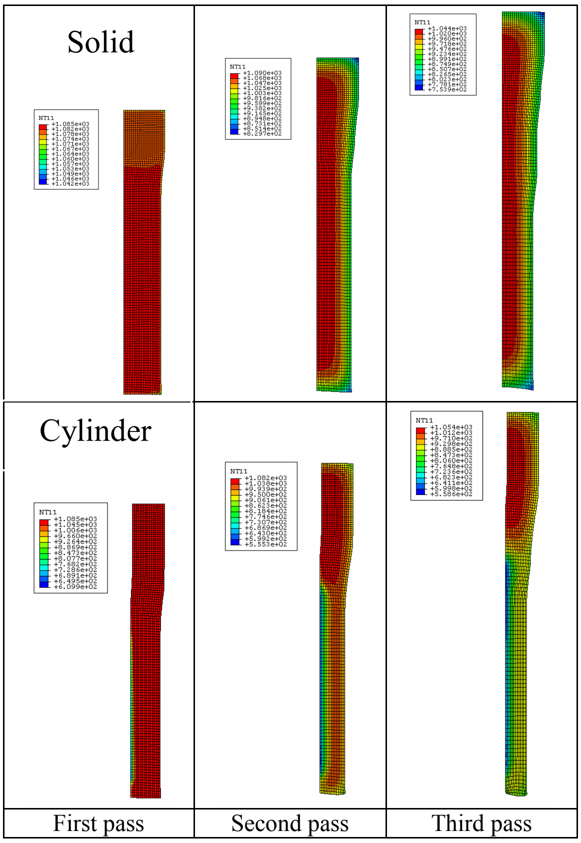


Fig8. Temperature distributions of products after each pass through axisymmetric simulation.

4 CONCLUSIONS

In this paper, the feasibility of using ABAQUS/explicit FEM package to model the radial forging of tubes and cylinders was investigated. Models were developed to determine material flow and temperature fields in RFP. The following conclusions were made based on the current investigation.

1. Deformations in the final tube product are larger and are more uniform than in the solid cylinder.

2. By increasing the number of passes, more uniform products can be produced.

3. Deformations at the outer and inner surfaces of the tube are larger than within the wall thickness.

4. There is a deformation gradient through the thickness of solid cylinder. The outer surface of the solid cylinder is more deformed than center.

5. Material properties are the same along the axial direction in both the tube and the solid cylinder.

6. The temperature gradient in the solid cylinder is higher than in the tube product. This results in more uniform material properties in tube products.

7. The highest components of stress and strain occur along the axial direction which causes improved properties along this direction.

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