Analysis of Rotary Forging of Sintered Preforms
Part II: Rotary Phase

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Abstract

The present paper, which is a continuation to the previous paper, deals with the theoretical and experimental analysis of the rotary phase of the sinter rotary forging. The rotary phase is dealt separately, since mushroom effect during deformation is neglected in the analysis. It is assumed that deformation during sinter rotary forging is an incremental process, in which initially a conical indent surface is created during indentation phase by axial movement of the upper conical die. Subsequently, this deformation is swept throughout the preform surface by angular movement of the upper conical die about its axis. The velocity field, strain rates, internal energy dissipation, frictional energy dissipation and average forging load during rotary phase of the deformation has been formulated in same manner as done in the part I of this paper with indentation phase. The experiments were conducted using aluminium sintered preforms and the results were compared with theoretical ones and were found to be in close agreement. It is assumed that the present work will be a great help in predicting the final rotary forging load and to investigate various deformation characteristics on the design of sinter rotary forging process.

Key Words: Sinter Rotary Forging, Conical Die, Rotary Phase, Angular Velocity

1. Introduction

Sinter rotary forging, an incremental, cost-effective forming process for the cold forging of intricate parts to net shape. The workpiece is gradually deformed between an upper conical die having orbital motion with an inclined rotating axis, and the lower die moving upwards. However, in the present analysis, the lower die is kept stationary and indentation feed too is given from top by the conical top die. The process has the potential for producing high-precision parts because of smaller forging forces and incrementally controlled deformation, especially in the cold forging of intricate parts to net shape. By limiting the contact area of the upper die and workpiece to a small portion of the preform surface, the advantage of load reduction offered by rotary forging over that of conventional forging has been reported to be from ten to thirty times [1].

The sinter rotary forging process is a fairly complicated deformation process and it is very difficult to obtain satisfactory results. In recent years, several attempts have been made to analyze and simulate the rotary phase of rotary forging process by the use of the upper-bound method [2–5]. The complexity in deformation was simplified by assuming the complete process to be segmented into two parts, i.e. indentation phase and rotary phase. The part I of the present paper dealt with the indentation phase and this part deals with the rotary phase of the sinter rotary forging process. In the present work, a kinematically admissible velocity field and corresponding strain rates, which can represent all of the velocity components in the deformation zone without velocity jumps for
rotary phase of the sinter rotary forging has been derived. From the velocity field and strain rates, the upper-bound rotary load was determined by minimizing the total external power consumption. The composite interfacial friction condition including both sliding and sticking frictions and yield criterion for porous material considered is same as in part I of the analysis. In order to confirm the validity of the proposed velocity field, experiments were carried out and the results were found to be in close agreement with the theoretical ones.

2. Deformation Characteristics and Assumptions

The deformation characteristics during sinter rotary forging i.e. die–workpiece interfacial friction conditions, densification during deformation, volume inconstancy, compatibility equation and yield criterion are considered to be exactly the same as in part I of the analysis. The assumptions are also the same.

3. Analysis of Rotary Phase

3.1. Velocity Field and Strain Rates

The velocity field and strain rates in the deforming region of preform under upper conical die rotating with angular velocity \( \omega \) and lower die stationary is assumed to be exponential and derived in similar manner as in part I of the present paper. Thus, velocity and strain rate field are given as:

\[
U_r = \left[ 1 - 2\eta \right] \frac{\beta e^{-\beta Z/h_r} \omega \sin \alpha (1 + \cos P\theta)}{\left(1 - e^{-\beta}\right) h_r} 
\]

(1)

\[
U_\theta = -\left[1 - 2\eta \right] \frac{\beta e^{-\beta Z/h_\theta} \omega \sin \alpha \sin P\theta}{P \left(1 - e^{-\beta}\right) h_r} 
\]

(2)

\[
U_z = -\left[1 - e^{-\beta Z/h_z} \right] \frac{\rho \omega \sin \alpha}{1 - e^{-\beta}} 
\]

(3)

The corresponding strain rates for indentation phase of rotary forging are given as:

\[
\dot{\varepsilon}_r = \frac{\partial U_r}{\partial r} = \left[ 1 - 2\eta \right] \frac{\beta e^{-\beta Z/h_r} \rho \omega \sin \alpha (1 + \cos P\theta)}{\left(1 - e^{-\beta}\right) h_r} 
\]

(4)

\[
\dot{\varepsilon}_\theta = \dot{\varepsilon}_{\theta 0} = \frac{1}{2} \left[ 1 - 2\eta \right] \frac{\beta e^{-\beta Z/h_r} \rho \omega \sin \alpha \sin P\theta}{\left(1 - e^{-\beta}\right) h_r} P 
\]

(5)

\[
\dot{\varepsilon}_z = \frac{\partial U_z}{\partial Z} = \frac{\beta e^{-\beta Z/h_z} \rho \omega \sin \alpha \sin P\theta \left( P^2 - 2 \right)}{\left(1 - e^{-\beta}\right) h_z P} 
\]

(6)

\[
\dot{\varepsilon}_{\theta z} = \frac{1}{2} \dot{\varepsilon}_{\theta 0} + \frac{1}{r} \frac{\partial U_\theta}{\partial r} = \left[ 1 - 2\eta \right] \frac{\beta e^{-\beta Z/h_r} \rho \omega \sin \alpha \sin P\theta \left( P^2 - 2 \right)}{\left(1 - e^{-\beta}\right) h_z} 
\]

(7)

\[
\dot{\varepsilon}_r = \frac{1}{2} \left[ \frac{\partial U_z}{\partial Z} + \frac{\partial U_\theta}{\partial r} \right] = \left[ 1 - 2\eta \right] \frac{\beta e^{-\beta Z/h_z} \rho \omega \sin \alpha \sin P\theta \left(1 + \cos P\theta \right)}{\left(1 - e^{-\beta}\right) h_z} 
\]

(8)

3.2. Power Dissipation and Die Load

The average die load may be obtained from the energy equations of ‘upper bound’ technique. The external power \( J^* \) supplied by the die platen during plastic deformation using upper bound approach is given as:

\[
J^* = \frac{2\sigma}{\sqrt{3}} \int \frac{1}{r} \left[ \dot{\varepsilon}_r \dot{\varepsilon}_r dV + \frac{\tau}{\sqrt{3}} |\Delta U| dS \right] 
\]

(10)

The first term on the right side denotes the rate of internal energy dissipation \( \dot{W}_r \) and the second term denotes the frictional shear energy losses \( \dot{W}_f \). The energy dissipation are computed by integrating the respective expressions \( \theta = \alpha' \) to ‘\( \pi \)’. The corresponding expression for radial distance is \( r = \left[ \frac{h}{2R_0 \tan \alpha} \right] \)

3.3 Internal Energy Dissipation

The internal energy dissipation during rotary phase
of sinter rotary forging may be given as:

$$W_i = \frac{\sigma_y}{\sqrt{3}} \left[ \frac{e_{i,j} e_{i,j}}{2} \right]^{1/2} dv \quad \text{where, } dv = (r dr d\theta dz)$$  \hspace{1cm} (11)$$

The above expression may also be expressed as:

$$W_i = \left( \frac{\sigma_y}{\sqrt{3}} \right)^{1/2} \left[ \frac{e_{i,j} e_{i,j}}{2} \right]^{1/2} (r dr d\theta dz)$$  \hspace{1cm} (12)$$

Substituting from eqs. (4)–(9), solving and simplifying, the expression for internal energy dissipation is given as:

$$W_i = \left[ \frac{2\sigma_y}{\sqrt{3}} (1 - 2n) \sin \alpha h^4 \right] \left[ \frac{1}{15\sqrt{6} (1 + \eta) \tan^3 \alpha} \right]$$

\[ \left\{ 1 + \frac{3\beta^2}{40 \tan \alpha} \left[ \tan^2 \frac{P_n}{2} + \frac{5}{3} \tan \frac{P_n}{2} + \frac{5 \tan \frac{P_n}{2} + \frac{43}{12}}{16} \right] \right\} 

\quad \left[ \frac{1}{16} \tan \frac{P_n}{2} + \frac{5}{4} \tan \frac{P_n}{2} + \frac{21}{16} \right]$$  \hspace{1cm} (13)$$

where, $$P = \frac{\pi}{2\alpha}$$

3.4 Frictional Energy Dissipation

The frictional shear energy loss during rotary phase of sinter rotary forging may be given as:

$$W_f = \int_{s} \tau |\Delta U| dS$$  \hspace{1cm} (14)$$

where, $$dS = (r dr d\theta)$$ and

$$\tau = \mu \left[ P + \rho \phi \theta \left( 1 - \frac{r_n - r}{nR_o} \right) \right]$$  \hspace{1cm} (15)$$

The deformation during sinter rotary forging consists both of radial and circumferential flow of preform material, the resultant magnitude of velocity along the direction of frictional shear stress is given as:

$$|\Delta U| = \left( U_r^2 + U_\theta^2 \right)^{1/2} \left| U_\theta - h \right|$$  \hspace{1cm} (16)$$

Substituting from eqs. (1), (2), (15) and (16), solving and simplifying, the expression for frictional shear energy dissipation is given as:

$$W_f = \left[ (1 - 2n) \mu B e^{+n} \theta h^4 \sin \alpha \right]$$

\[ \frac{1}{40(1 + n)(1 - e^{-n})^3 \tan^2 \alpha} \]

\[ \left\{ \frac{P_n}{80 R_o \tan \alpha} \left[ \tan \frac{P_n}{2} + \frac{5}{3} \left( 1 + 8P^2 \right) \tan \frac{P_n}{2} \right] \right\} 

\quad \times \left[ \frac{1}{2} \tan \frac{P_n}{2} + \frac{8}{3} \left( 1 + 5P^2 \right) \right]$$  \hspace{1cm} (17)$$

3.5 Average Rotary Forging Load

The average rotary forging load may be obtained by substituting the energy eqs. (13) and (17) in eq. (18) and solving subsequently.

$$J^* = \left[ (F_r + W_d) \right] = \left[ (F_r + R_o \omega) / A \right]$$  \hspace{1cm} (18)$$

$$F_r = \frac{2 (W_i + W_f) A}{R_o \omega}$$  \hspace{1cm} (19)$$

4. Results and Discussion

The various deformation parameters considered during analysis of rotary phase of the rotary forging are same as in case I, except that the present analysis includes angular velocity of upper conical die i.e. $$\omega = 3.7, 14.5$$ and 37.0 rad/sec respectively. Figure 1 shows variation of final rotary load with skew contact angle of upper conical die for different angular velocity of die and friction conditions. The nature of variation is same as in case I i.e. variation of indentation load with skew contact angle during indentation phase of sinter rotary forging. It is evident from the figure that forging load is low for higher skew contact angle, which signifies decrease in load requirements when upper conical die used during rotary forging has smaller cone angle i.e. higher skew contact angle. This is due to the fact that upper conical die with smaller cone angle will have smaller contact area between die and preform surface. This confirms the advantage of load reduction of
fered by rotary forging over that of conventional forging by limiting the contact area between upper die and pre-form surface. The forging loads are higher for higher angular velocity of die and high friction conditions. This indicates that higher deformation is possible with high die velocity at higher forging loads. The forging loads for low friction conditions are smaller due to better lubrication conditions leading to better metal flow.

Figure 2 shows variation of rotary forging load with indentation depth for different angular die velocity and friction condition during rotary phase of sinter rotary forging. It is evident from the figure that indentation depth increases with increase in indentation load and friction condition. The nature of variation is entirely different from case I, as friction conditions dominates over the angular die velocity in the present case. In case I, the load curves for same die velocity were closer to each other and the curves for high friction condition were higher. In the present case, it is vice versa. As seen from the figure, the loads are comparable for same friction conditions and curves for same friction condi-

![Figure 1. Variation of final rotary load with skew contact angle of rotary die.](image1)

![Figure 2. Variation of rotary forging load with indentation depth.](image2)
tions are closer to each other irrespective of the die velocity. This is due to better metal flow condition under lubrication i.e. low friction conditions during rotary phase as compared to the indentation phase. The hollow circles represent the experimental data for rotary forging load at different indentation load under dry friction conditions i.e. \( \mu = 0.30 \) approximately. It is clearly evident from the figure that the experimental data are in close agreement with theoretical ones and thus, confirms the validity of velocity field, strain rates and various energies computed during present analysis of indentation phase of rotary forging. Figure 3 shows preforms with increase in indentation area due to increase in rotary forging die load under dry lubrication conditions during rotary phase of sinter forging. Figure 4 shows variation of preform height reduction in percentage with angular velocity of upper conical die at different rotary forging loads and friction conditions. It is evident from figure that preform height reduction increases rapidly with increase in die velocity at the start of deformation and remains fairly constant thereafter. Also, it is clear from the figure that preform height reduction increases with rotary forging load at constant angular velocity of the upper conical die. The preform height reduction is more in case of low friction conditions as compared to high friction condition at constant angular velocity and forging load. This is because of better metal flow conditions during low friction conditions.

Figure 5 shows variation of relative density of preform with final rotary forging load during rotary phase of sinter rotary forging for different angular velocity of die and friction conditions. It is evident from the figure that the relative density of preforms increases rapidly with rotary forging load during initial phase of deformation and remains fairly constant thereafter. This is because of rapid closing of inter-particle pores within the preform initially. The experimental evidence during sinter forging reveals that compaction i.e. closing of pores and compression i.e. deformation takes place simultaneously within the preforms. Initially, the compaction or densification dominates the compression till its relative density becomes comparable with that of wrought metals and hen-

**Figure 3.** Preforms with increase in indented area during rotary phase.

**Figure 4.** Variation of height reduction of preform with angular velocity of upper conical die.
ce, deformation is appreciable low. After its relative density approaches to about 0.90–0.95 approximately, the deformation dominates the closing of pores. The increase in relative density is higher in case of low friction condition due to better metal flow condition. The hollow circles represent the experimental data for change of relative density of preform with final rotary forging load at dry friction conditions for various angular die velocities considered during present analysis. It is seen from the figure that the experimental and theoretical results are fairly comparable, which confirms the validity of the exponential velocity field and strain rates derived in the present analysis from the compatibility equation formulated from the yield criterion of the porous materials.

5. Conclusions

In the present work a kinematically admissible exponential velocity field and corresponding strain rates have been formulated from the yield criterion for porous materials during rotary phase of sinter rotary forging. The theoretical average rotary forging load was determined from the velocity field and strain rates based on upper bound approach. The experiments were conducted using aluminium powder preform under dry lubrication conditions at room temperature and the effects of preform height reduction, indentation depth, angular die velocity, skew contact angle and interfacial friction conditions were critically studied and the results were compared also. The experimental results were found in close agreement with theoretical ones confirming validity of the formulations of velocity field and assumptions made in the present analysis. It also confirmed the validity of the compatibility equation used in the present analysis, which was derived from the yield criterion for porous materials. It is believed that the present work can be very useful for design engineers to predict the forming load requirements during deformation of powder preforms and for researchers to carry out further investigations.

References


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