A study on aluminum metal matrix preforms forging into double-hub flange

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Abstract. The present article presents investigation of deformation characteristics during forging (closed-die) of SiCp AMC. The preform (cylindrical) fabricated via liquid metal stir casting manufacturing route were located centrally in closed-die set with respect to its axis and forged into axi-symmetric double-hub flange component. Initial experiments were conducted to examine the mechanical characterization of the AMC preforms under consideration, which also included investigations into interfacial frictional conditions and stress-strain behaviour of the AMC material. Under a controlled die-travel till the die corners were filled completely, during forging of the preforms, corresponding height reductions and die loads were recorded. The complete deformations were considered in two stages, i.e. free barreling and constrained distortion stages. The theoretical expressions (generalized using ‘Upper Bound’ technique) for strain rates, velocity field, various energy dissipations along with average die loads for all the deformation modes considered in the present study were formulated. The variation in die loads, die cavity fills and energy dissipations due to the effect of preform aspect ratio and die velocity were critically examined and experimentally compared the results.

Keywords. Closed-die forging, SiCp reinforced Aluminium metal matrix composite, Axi-symmetric double-hub flange component, Average die load, Die cavity fill.

1. Introduction

In last two decades, hybridizing composites, especially metal matrix has gained the researchers’ attention due to its enhanced engineering material properties. The advantage of adding reinforcements is the proper transfer and uniform distribution of external load. Thus, these materials are now-a-days used to manufacture numerous engineering components via various manufacturing routes [1, 2]. Closed-die forging is one such manufacturing route, which is regarded as complex deformation process due to inherent unsteady state of deformation primarily due to non-uniform constraint metal flow along the die corners. The hybrid die-preform-container interfacial frictional conditions further makes the deformation process difficult to analysis [3-5].

The present paper aims at studying the forging of Aluminium metal matrix composite (AMC) cylindrical preforms reinforced with Silicon Carbide particulate (SiCp) into axi-symmetric double-hub-flange components within closed-die sets. The AMC was fabricated via liquid metal stir casting manufacturing route where the matrix metal was LM6 Aluminium casting alloy and reinforcement material was Silicon Carbide particles. The objective of the present research was to integrate a composite material having enhanced mechanical properties and then subsequently mechanically forge it to fabricate
an industrial product for automotive applications, i.e. double-hub flange component.

Figure 1 gives the schematic representation of a forging (closed-die) process where the preforms are positioned coaxially within die-container. Free barreling and constraint deformations are two sequential stages for the complete deformation. The free barreling stage consists of preform bulging till its vertical surfaces touches the middle of die-container sidewalls similar to an open-die forging process [Refer Figure 2(a)], whereas keeping in mind formation of corners of preform and filling of die corners occurrence, bulged preform’s deformation constrained in the second stage. The straight lines in figures 2(b) illustrates the approximated preform’s profile (bulged) for ease of analysis.

Figure 1. Preform Location
Figure 2. Deformation Stages

In the present theoretical analysis, the quarter of preform is considered due to symmetry along the axes which is further divided into deforming zones on the basis of velocity discontinuity regions. Finally, three different combinations of deformation zones have been considered leading to three deformation modes. The ‘Upper Bound’ approach was the basis on which the expressions for strain rates, frictional shear, velocity field, and inertia energy dissipations along with average die load and die cavity fills were formulated. The corresponding experimental investigations were performed by fabricating the preforms and forging them within the closed-die sets. Also, critically examined the variation of die loads and die cavity fills due to location of preform. Aside, compared both theoretical and experimental results. For the analysis of the forging (closed-die) operations at cold conditions in order to develop precision net-shape components, the ongoing analysis is supposed to be beneficial.

2. Basic Experimental Work
The present research utilized liquid metal stir casting as the viable method for fabrication of AMC under consideration due to operational simplicity and lower processing cost [6]. The Aluminium alloy (LM6) was melted in furnace (electric resistance) with Mg (5 wt% having particles < 500μ) addition for bonding (strong) between reinforcements and base metal. It helps in decreasing the surface energy of molten metal by reducing the wetting angle between the constituents. The pre-heated reinforcements (SiC particles < 400μ) were added to the molten metal (at a pouring temperature of about 900°C) and stirred (500 rpm) using an impeller (mechanical) as shown in figure 3. An optimum temperature of 700°C was maintained during the mixing process. The mixture was poured in a silica mould and allowed to cool to room temperature. The final cast was obtained by breaking the mould and all samples were solution heat-treated at 500 °C for about one hour in an electric furnace as per ASM standards to ensure uniform microstructure and mechanical properties [7]. The details of LM6 Aluminium alloy and SiCp reinforcements along with
dimensions of preform and final forged components are shown in table 1.

The mechanical characterization of AMC preforms was performed using standard disc specimens having 20 mm height and 20 mm diameter and results shown in figures 4(a) - (e). The samples having 5.0, 7.5, 10.0 and 13.0 wt% SiCp were fabricated for basic experimental investigation planned under the present research work.

![Electric resistance furnace with customized mechanical impeller](image)

**Figure 3.** Electric resistance furnace with customized mechanical impeller

| Elements | Percentage (%) | Density (gm/cm³) | Mesh Size of Particle (Average) | Thermal Conductivity (W/m-K) | Specific Heat (J/Kg-K) | Preform Dimension | Component Dimension |
|----------|----------------|------------------|-------------------------------|-----------------------------|------------------------|------------------|-------------------|
| Si       | 10-13          | 2.66             | 3.2                           | 155                         | 960                    | 600              | 1300              |
| Cu       | 0.1            |                  | 400                           |                             |                        |                  |                   |
| Mg       | 0.1            |                  | 100                           |                             |                        |                  |                   |
| Fe       | 0.6            |                  |                                |                             |                        |                  |                   |
| Mn       | 0.5            |                  |                                |                             |                        |                  |                   |
| Ni       | 0.1            |                  |                                |                             |                        |                  |                   |
| Zn       | 0.1            | Disc             | Cylindrical                   | R₀ = 15 mm                  | R'₀ = 10 mm            |                  |                   |
| Pb       | 0.1            | D = 20 mm        | D = 20 mm                     | H₂₀ = 20 mm                 | H'₂₀ = 40 mm           |                  |                   |
| Sb       | 0.05           | H = 20 mm        | H = 40 mm                     |                             |                        |                  |                   |
| Ti       | 0.2            |                  |                                |                             |                        |                  |                   |
| Al       | Remaining       |                  |                                |                             |                        |                  |                   |

From plot 4(a), it may be noted that hardness of AMC preform is directly proportional to SiCp addition. It was also found that the rate change of hardness is initially high but becomes constant after a critical wt% of SiCp (which is found to be 10 wt% SiCp additions). From figures 4(b) and (c), it is evident that the impact toughness increases whereas elongation (measure of ductility) decreases with addition of SiCp. Figure 4(d) and (e) shows plots of compressive, ultimate tensile and yield strengths of AMC preforms respectively. It can be observed that these strengths increase with the addition of SiCp and the highest value is observed for 13.0 wt% SiCp. Similar trend was noticed in the earlier plots, which indicated that there is a critical limiting value of reinforcements which can be added in the metal matrix.
without compromising mechanical properties of AMC. The flow behaviour of AMC was investigated by performing standard compression tests, where standard disc-shaped preforms were forged on a hydraulic press at room temperature under lubricated interfacial frictional conditions (Teflon sheets were used as a lubricant). The forging load was recorded for various intermittent deformations of preform which was utilized for estimating the effective stress and strain data as shown in figure 4(f). The stress-strain curve was assumed to follow the generalized power law equation expressed as $\sigma = K \varepsilon^n \text{MPa}$, where $K$ and $n$ were found as 269.31 MPa and 0.28 respectively for 13.0 wt% SiCp samples.
The interfacial friction factor was measured by conducting standard ring compression test using annular ring preforms having dimensional ratio of outer diameter, inner diameter and height as 6:3:2. The experiments were performed under dry and lubricated frictional conditions and conventional shear friction model expressed as $f_{\text{friction}} = mk$ was used to estimate the coefficient of friction. The plots for percentage change in inner diameter with height reduction was mapped with standard calibration curves and values of ‘k’ (shear flow stress) and ‘m’ (friction factor) were found to be 0.33 and 0.15 respectively.

Finally, two groups of AMC preform having 5.0 and 13.0 wt% SiCp were utilized for closed-die experiments. These preforms were forged within the closed-die sets mounted on a hydraulic press and data for deformations along with forging loads were recorded. In all the experimental runs, deformation was carried under lubricated interfacial friction conditions (with grease as lubricant) till the end of forging process, i.e. complete filling of die-cavities. was fabricated having two rigid closed die-halves comprising of, and as shown in figure 5(a) illustrates combination of various components of the forging die, i.e. container, counter lower punch along with its upper punch considered in the present research. There is a recess-cavities in the dies which is cylindrical in nature & similar to hub’s diameter and length in order to ease and maintain precise location of preform. Until the occurrence of completely filling of die corner the required die loads were noted for different height reduction (die travels) during processing (forging) of this preform. The die’s unfilled vol % was computed considering the of the preforms’ (deformed) dimensions post removal from the die set. Post forging, through different phases, figure 5(b) shows the deformed preforms.

**Figure 4.** Mechanical characterization curves for SiCp reinforced AMC samples

(e). Yield and UTS vs SiCp Wt%

(f). Stress-Strain Curve of SiCp AMC
3. Theoretical Analysis

‘Upper Bound’ strategy used for analysis (theoretical) in the present research and to simply the analysis, few assumptions were made [8, 9]:

- The preform free barreling was neglected and only constraint deformation stage, i.e. complete filling of die-cavity, as well as, formation of preform edges has been considered. Towards the end of complete filling of die-cavity, the die load in forging was computed.
- The rotation of preform (i.e. circumferential flow) is ignored and the preform surface was assumed to be straight during the entire deformation process.
- The compatibility conditions were formulated from ‘Volume Constancy’ principle as AMC material was considered incompressible, which is expressed as:
  \[ \dot{e}_r + \dot{e}_\theta + \dot{e}_z = 0 \]  
  (1)

- The suitable combination of both frictions, i.e. sticking and sliding is responsible for development of ‘composite interfacial friction’ at die-workpiece-container which is expressed as:

  \[ \tau = \mu \left( P_v + \varphi_h \left[ 1 - \left( \frac{R_m - r}{nR_o} \right) \right] \right) \]  
  (2)

Where, the approximated radius of sticking zone, i.e. \( R_m \) can be depicted as:

\[ R_m = R_o - \frac{H_o}{2\mu} \ln \left( \frac{1}{\mu \sqrt{3}} \right) \]  
  (3)

- The preform surface was divided into deforming and dead zones based on redundant energy dissipation and three different configurations of deformation modes have been considered separately for analysis.

Figures 6 (a) - (c) shows various deformation modes considered in the present analysis. In case of deformation mode-I; zones 1 and 3 are considered to be dead, whereas for deformation mode-II only zone 1 is assumed to be dead. Furthermore, there are five different zones of preform including dead zones 1 and 3 (assumed) for mode-III deformation.
Figure 6. Deformation modes based on the division of preform surface

The kinematically admissible velocity field and strain rates for each metal flow zones for all the three deformation modes were formulated separately as shown in the Appendix. The energy dissipations along with average die load were formulated separately satisfying these velocity field and strain rates.

3.1 Deformation Mode – I

3.1.1 Zone – 2

\[
W_e = \left[ \frac{\sqrt{5} \pi \sigma_0 U R_0^2 (2 \psi + 1)}{3 \sqrt{3}} \right]
\]

\[
W_{t_1} = \left\{ \frac{\pi \mu R_0^3 (\psi^2 - \lambda^2)}{3h} \right\} \left[ P_{av} + \varphi_0 \left( \frac{1 - R_m}{6 \pi R_0} \right) + \frac{\varphi_0}{8 \pi} \left( \frac{\psi^2 - \lambda^2}{\psi^4 - \lambda^4} \right) \right]
\]

\[
W_{t_2} = \left\{ \frac{\pi \mu R_0 (H_0 - h)^2 U}{h} \right\} \left[ P_{av} + \varphi_0 \left( \frac{1 - Z_m}{n H_0'} \right) + \left( \frac{2 \varphi_0 (H_0 - h)}{3 n H_0'} \right) \right]
\]

\[
W_s = \left\{ \frac{\pi \rho_s (1 - \psi) R_0^2 U}{10} \right\} \left[ \frac{R_0^2 \left( 4 \lambda^2 + 3 \lambda^2 + 2 \lambda + 1 \right) U^2}{8 h^2} + \left[ (1 + 4 \lambda) U^2 \right] + \left[ \frac{20 \lambda (2 \lambda + 1) U}{3} \right] \right]
\]

3.2 Deformation Mode – II

3.2.1 Zone - 2

\[
W_i = \left[ \frac{\sqrt{2} \pi \sigma_0 R_0^2 \psi^2 U}{\sqrt{2}} \right]
\]
\[ W_{r1} = \left( \frac{\pi \mu UR_0^3 (\psi^3 - \lambda^3)}{3H_0'} \right) \left\{ P_{\psi} + \varphi_0 \left( 1 - \frac{R_m}{6n\psi R_0} \right) + \left\{ \frac{\varphi_0}{8n\psi} \left( \frac{\psi^4 - \lambda^4}{\psi^3 - \lambda^3} \right) \right\} \right\} \]

\[ W_{r2} = 0 \]

\[ W_t = \left( \frac{\pi \rho \psi^2 R_0^2 U}{3} \right) \left\{ \frac{3\psi^2 R_0^2}{16H_0'^{\psi^2}} - 1 \right\} U^2 + 3\dot{U}H_0' \] (11)

### 3.2.2 Zone - 3

\[ W_i = \left[ \frac{\sqrt{2\pi \sigma_o (H_0' - h)^2 R_0^2 (1 - \psi)^2 U \alpha^{1/2}}}{2\sqrt{3}H_0'^{\psi^2}} \right] \] (12)

\[ W_{r1} = 0 \]

\[ W_{r2} = \left( \frac{\pi \mu R_o (H_0' - h)^2 U}{H_0'^{\psi^2}} \right) \left\{ P_{\psi} + \varphi_0 \left( 1 - \frac{Z_m}{nH_0} \right) + \left\{ \frac{2\varphi_0 (H_0' - h)}{3nH_0'} \right\} \right\} \] (13)

\[ W_t = \left( \frac{\pi \rho R_o^2 (1 - \psi^2)}{3} \right) \left\{ \frac{3R_o^2 (1 + \psi^2)}{16(H_0' - h)^2} - 1 \right\} \left\{ \frac{H_0' - h}{H_0'} \right\}^6 U^2 + 3\dot{U} (H_0' - h) \] (15)

### 3.2.3 Zone - 4

\[ W_i = \frac{\pi \sigma_o (2H_0' - h) R_0^2 (4 - \psi - 7\psi^2) U}{6H_0'} \] (16)

\[ W_{r1} = W_{r2} = 0 \]

\[ W_t = \frac{\pi \rho (1 - \psi) R_0^2 (2H_0' - h)^2 U^3}{6H_0'^{\psi^2}} \left\{ \frac{8h^2}{6hH_0' (2\psi + 1) \dot{U}} + \frac{3(3\psi^3 + 3\psi^2 + \psi - 1)R_0^2}{(2H_0' - h) U^2} \right\} \] (18)

### 3.3 Deformation Mode – III

#### 3.3.1 Zone - 2

\[ W_i = \left[ \frac{\sqrt{2\pi \sigma_o R_0^3 \psi^3 U}}{\sqrt{3}} \right] \] (19)

\[ W_{r1} = \left[ \frac{\pi \mu UR_0^3 (\psi^3 - \lambda^3)}{3(1 - \lambda) h + \lambda H_0'} \right] \left\{ P_{\psi} + \varphi_0 \left( 1 - \frac{R_m}{6n\psi R_0} \right) + \left\{ \frac{\varphi_0}{8n\psi} \left( \frac{\psi^4 - \lambda^4}{\psi^3 - \lambda^3} \right) \right\} \right\} \] (20)

\[ W_{r2} = 0 \]

\[ W_t = \left( \frac{\pi \rho \psi^2 R_0^2 U}{3} \right) \left\{ \frac{3\psi^2 R_0^2}{16(1 - \lambda) h + \lambda H_0'^{\psi^2}} - 1 \right\} U^2 + 3\dot{U} \left[ (1 - \lambda) h + \lambda H_0'^{\psi^2} \right] \] (22)
3.3.2 Zone - 4

\[ W_i = \left( \frac{\sqrt{2} \pi \sigma_o \lambda^2 (H_0' - h)^2 R_o^2 (1 - \psi^2)}{\sqrt{2} [1 - \lambda \lambda_0 + \lambda H_0']} \right) \]

\[ W_{f_1} = 0 \]

\[ W_{f_2} = \left( \frac{\pi \mu R_o \lambda^3 (H_0' - h)^3 U}{[1 - \lambda \lambda_0 + \lambda H_0']^2} \right) \left\{ \rho \varphi_o \left( 1 - \frac{Z_{m}}{n H_0'} + \frac{2 \varphi_o \lambda (H_0' - h)}{3 n H_0'} \right) \right\} \]

\[ W_a = \left( \frac{\pi \rho \lambda^2 (1 - \psi^2) U}{3} \right) \left\{ \left[ \frac{3 R_o^2 (1 + \psi^2)}{16 \lambda^2 (H_0' - h)^2} - 1 \right] \left[ \frac{\lambda^6 (H_0' - h)^6}{[1 - \lambda \lambda_0 + \lambda H_0']^6} \right] U^2 + 3 \lambda \lambda_0 (H_0' - h) \right\} \]

3.3.3 Zone - 5

\[ W_i = \left( \frac{\pi \sigma_o \chi R_o^2 U}{6} \right) \]

\[ W_{f_1} = W_{f_2} = 0 \]

\[ W_a = \left( \frac{\pi \rho \lambda^2 (1 - \psi) R_o^2 U^3}{6} \right) \left\{ \left[ \frac{3 \chi R_o^2 \left[ 4 \psi^4 + 3 (\psi^2 + 1)(\psi - 1) \right]}{8 (1 - \psi)} \right] + \frac{2 R_o \chi \lambda (2 \psi + 1)(1 - 3 \chi)}{h U^2} + 2 \lambda \lambda_0 (2 \psi + 1) \right\} \]

Where, \( \psi = \left( \frac{S}{R_o} \right), \lambda = \left( \frac{R_0}{R_o} \right) \) and \( \chi = \left[ \frac{2 + \frac{h}{\lambda (H_0' - h)}}{\lambda (H_0' - h)} \right] \)

The total energy dissipation and subsequently average die load may be computed from following equations [10]:

\[ J^* = 4 \sum_j \left( W_i + W_{f_1} + W_{f_2} + W_a \right)_j \] (j = metal flow zone)

\[ F_{av} = J^* \left( \frac{U}{U} \right)^{-1} A_{av} \]

4. Results and Discussion

Figure 7 shows that preforms with higher aspect ratio and lower wt% SiCp exhibit higher height reduction at same die load. This indicates that deformation in slender preforms are higher as compared to shorter ones under same die load, which may be attributed because of the geometrical difference of unfullied die corners. Also, preforms with high wt% SiCp requires larger die load to deform as it exhibit higher compressive strength. The variations in figure 8 are similar to previous one and it may be observed that the rate of preform height reduction is predominant during initial deformation compared to the end of forging operation. This is because preform vertical surface is allowed to bulge freely within die space due to non-constraint deformation. Later, when preform surface comes into contact of die-container walls; the contact area along with resistance against deformation grows asymptotically due to high container-preform interfacial friction. Thus, higher die loads are required to squeeze fill the die cavities, especially
during the end of forging operation.

![Figure 7.](image)

![Figure 8.](image)

Figures 9 (a) - (c) illustrates the conditions needed to ensure corner fills in the die with various volume (cavity) to volume (component) ratio (aspect ratio) along with its corresponding load (die). Towards the end of the cavity fills in the die, i.e. end of forging process high constraint deformation occur which lead to exponentially high ‘die load’. The die-container wall’s contact area becomes large due to aspect ratios (high) that leads to high energy (friction shear) dissipations which is in turn responsible for load curves (high) as it can be seen in the figure. Also, to fill the die cavities the preforms having high wt% SiCp requires the die load of high value due to higher compressive strength and interfacial friction conditions. Hence, it’s recommended that closed-die forging operations should be carried under lubricated frictional conditions to get defect-free components. Additionally, towards the end of the cavity fills in the die, i.e. end of preform’s forging process, aspect ratio’s effect on die load ruled out by wt% effect of SiCp. This is due to the dominant effect of compressive strength of AMC on the die load requirement and redundancy of the preform aspect ratio during extreme constraint deformation stage. The results were found in close agreement with the experimental results validating the present theoretical analysis. Also, from figure 9(c), it may be inferred that die load estimates are higher for deformation mode-III compared with other two deformation modes. This indicate that while designing the mechanical processing equipment, e.g. closed-die sets and forging presses; deformation mode-III should be used as it will provide higher degree of design safety. This will ensure fabrication of defect-free final forged components.

The figure 10 illustrates the different die cavity fill conditions with and without inertia effects along with die load variation i.e. load factor comparison. It’s value increases and become asymptote with y-axis with the increase in the die fills which is evident from figure. Also, it’s higher for high wt% SiCp and deformation mode-III. This occurs due resistance (sharp decrease) against preform material’s deformation due to time of contact (extremely short). The strength of AMC decreases because during deformation the heat generated does not comes out quickly. Additionally, it may be observed that the forging load for deformation mode-III is higher as compared with other deformation modes and thus, it is practical in forecasting the die load accurately.
5. Conclusions
The important conclusions drawn from the above investigations are as follows:

- The slender preforms exhibit higher reductions in height at the same die load due to the configuration of unfilled die corners. This is due to the variance in preform barreling as these preforms make contact with die container walls early compared to the shorter ones. This creates large interfacial contact area leading to higher interfacial friction shear energy dissipations.

- The rate change of preform height reduction is high during initial deformation compared to the end of forging operation. This is because the preform vertical surface can freely bulge within the die-container space due to zero interfacial frictional resistance. Later, when preform vertical surface touches the die-container walls and contact area grows asymptotically with deformation leads to high resistance against deformation due to increased container-preform interfacial friction conditions.

- The preforms with high wt% SiCp under high interfacial friction conditions require greater die load to deform due to high compressive strength. Thus, higher die loads are required to squeeze fill the die cavities, especially during the end of forging operation. Hence, it’s recommended that all closed-die forging operations should be preferably carried under lubricated frictional conditions in
order to get defect-free components.

- The effect of wt% SiCp dominates over the preform aspect ratio on die load requirements especially when the die cavities are just about to be filled. This is due to the dominant effect of compressive strength of AMC on the die load requirement including the redundancy of preform aspect ratio.

- The deformation mode-III gives better realistic approximation of die load requirements related to other deformation modes and must be preferred during the design of mechanical processing equipment in order to fabricate defect-free forged components.

- The effect of die velocity and inertia effect on the die load requirement has been demonstrated using load factor \( \zeta \), which increases exponentially and become asymptote with the y-axis with die fills. This is due to forging operation at higher die speed. It reduces the contact time under load. Thus during plastic deformation, the internal heat generated does not escape quickly. In result the resistance of composite material against deformation reduces.

It is expected that the present research will be highly useful for researchers, practicing engineers and scientists for understanding and carrying further research work in the field of precision closed-die forging of AMCs for fabrication of defect-free industrial components.

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## Appendix

### Deformation Mode – I

**ZONE - 2**

| Boundary Conditions | Velocity Field | Strain Rates |
|---------------------|----------------|--------------|
| $U_z = 0$ at $z = (H_0 - h)$ | $U_z = \frac{U}{2h}$ | $\dot{\varepsilon}_z = \dot{\varepsilon}_{zz} = \frac{U}{2h}$ |
| $U_x = -U$ at $z = H_0$ | $U_x = 0$ | $\dot{\varepsilon}_x = \dot{\varepsilon}_{xx} = 0$ |

### Deformation Mode – II:

**ZONE - 2**

| Boundary Conditions | Velocity Field | Strain Rates |
|---------------------|----------------|--------------|
| $U_z = -U$ at $z = H_0$ | $U_z = 0$ at $z = 0$ | $U_z = \frac{U(H'_0 - h)}{H'_0}$ at $z = (H'_0 - h)$ |
| $U_x = 0$ at $z = 0$ | $U_x = 0$ | $U_x = -U$ at $z = H_0$ |

### Deformation Mode – III:

**ZONE - 4**

| Boundary Conditions | Velocity Field | Strain Rates |
|---------------------|----------------|--------------|
| $U_z = 0$ at $z = [H'_0 - h](1 - \lambda)$ | $U_z = 0$ at $z = [H'_0 - h](1 - \lambda)$ | $U_z = -\frac{\lambda(H'_0 - h)}{h + \lambda(H'_0 - h)}$ at $z = (H'_0 - h)$ |
| $U_x = -U$ at $z = H'_0$ | $U_x = 0$ | $U_x = -U$ at $z = H'_0$ |

### Deformation Mode – IV:

**ZONE - 5**

| Boundary Conditions | Velocity Field | Strain Rates |
|---------------------|----------------|--------------|
| $U_z = \frac{U}{2[H'_0 - (H'_0 - h)(1 - \lambda)]}$ | $U_z = \frac{U}{2[h + \lambda(H'_0 - h)]}$ | $\dot{\varepsilon}_z = \dot{\varepsilon}_{zz} = \frac{U}{2(h + \lambda(H'_0 - h))}$ |
| $U_x = -U$ at $z = H'_0$ | $U_x = 0$ | $\dot{\varepsilon}_x = \dot{\varepsilon}_{xx} = 0$ |

### Deformation Mode – V:

**ZONE - 6**

| Boundary Conditions | Velocity Field | Strain Rates |
|---------------------|----------------|--------------|
| $U_z = 0$ at $z = [(H_0 - h)(1 - \lambda)]$ | $U_z = 0$ at $z = [(H_0 - h)(1 - \lambda)]$ | $U_z = -\frac{\lambda(H_0 - h)}{h + \lambda(H_0 - h)}$ at $z = (H_0 - h)$ |
| $U_x = -U$ at $z = H_0$ | $U_x = 0$ | $U_x = -U$ at $z = H_0$ |
Nomenclature

\[ \begin{align*} 
U_{ij} & \quad \text{velocity field} \\
\dot{\varepsilon}_{ij} & \quad \text{strain rates} \\
U & \quad \text{die velocity} \\
\sigma_0 & \quad \text{flow stress} \\
P_{av} & \quad \text{average die pressure} \\
F_{av} & \quad \text{average die load} \\
H_0 & \quad \text{preform initial height} \\
\rho_0 & \quad \text{preform relative density} \\
R_0 & \quad \text{flange radius} \\
R'_0 & \quad \text{hub radius} \\
\end{align*} \]

\[ \begin{align*} 
W_i & \quad \text{internal energy dissipation} \\
W_{ri} & \quad \text{die-workpiece frictional energy dissipation} \\
W_{cl} & \quad \text{die-container frictional energy dissipation} \\
J^* & \quad \text{total external energy supplied by press} \\
\tau & \quad \text{interfacial frictional shear stress} \\
\end{align*} \]

Subscripts

\[ \begin{align*} 
r & \quad \text{radial} \\
\theta & \quad \text{circumferential} \\
Z & \quad \text{vertical} \\
\end{align*} \]