ABSTRACT

The paper presents an investigation into the problem of shape heading under low-velocity dynamic forging conditions where the initially circular aluminum porous specimen clamped at one of its ends, is headed into a circular shaped head rivet. Yield criterion, friction law, chosen velocity field an upper bound approach have been considered to develop a mathematical model for the relative average forging pressure on the specimen at different strain rate. The specimens were prepared and subjected to rivet head forging process at different strain rates: 1.5, 50, 100 and 150 mm/min under lubricated end conditions. Parametric analysis giving the variation of the relative average forging pressure versus percentage reduction in height of the specimen during rivet head forging process was presented graphically. Theoretically and experimentally obtained values of forging load versus percentage reduction in height of the specimen during the process were plotted and a good correlation was observed. Strain rate effect on forging load during circular rivet head forming process versus percentage reduction in height were presented graphically, analyzed and discussed critically.

Keywords— Porous aluminum specimen, rivet shaped heading, strain rate, yield criterion,

I. INTRODUCTION

Sintered metal powder porous specimen forging has the advantages associated with conventional powder metallurgical processes, as the additional strength is provided by the elimination of porosity as discussed by Cull (1970) [1]. Jha and Kumar (1988) [2] investigated the influence of powder particle size, compacting pressure, sintering temperature, and forging parameters on relative density of the specimen along with the deformation characteristics and fracture mechanisms during the cold forging of sintered iron powder specimen under axisymmetric conditions.

Chitkara and Bhutta (2001) [3] had dealt the problem for solid circular rod to head into a triangular, hexagonal, and octagonal shaped heads. The shape heading was accomplished in three stages i.e. the upsetting stage, cavity filling or head forming stage and flash formation stage. They showed in their investigation that in dynamic shape heading of triangular, hexagonal, and octagonal shaped heads, the dynamic die loads are 20-40% higher than the static loading. Singh and Jha (2001) [4] have analyzed the dynamic effects during high speed forging of sintered porous specimens by energy method for axisymmetric and plain strain conditions. They have shown that die velocity has significant effect on deformation characteristics. Ranjan and Kumar (2004) [5] presented a generalized solution to determine die pressure for high speed forging of N-sided polygonal sintered powder disc. Ranjan and Kumar (2004) [6] used an upper bound approach to determine the die pressure in closed die forging of hexagonal porous specimen. Sumathi and Selvakumar (2012) [7] have investigated the workability of sintered copper-silicon carbide specimens during cold axial upsetting. They showed that strength property is very high at 5% of SiC with copper and with higher value of SiC addition, the initiation of crack appeared at a low axial strain. Verma et.al (2013) [8] have investigated the deformation characteristics during open-die forging of silicon carbide particulate reinforced aluminum metal matrix composites (Si-Cp AMC) at cold conditions. No one has carried out investigation on cold forging of rivet shaped head from cylindrical sintered porous specimen at different strain rates.

The problem of shape heading under low-velocity dynamic forging conditions has been investigated. Initially circular sintered aluminum porous specimen
clamped at one of its ends is headed into a circular shaped head rivet at different strain rates, considering upsetting and head formation in one stage only. A mathematical model has been developed to show the variation of the relative average forging pressure versus percentage reduction in height during the head forming process. The appropriateness of the obtained theoretical results has been verified experimentally.

II. THEORY

Yield Criterion for Porous Metallic Specimen

Basic Assumptions:-

- The material of the porous specimen is isotropic rigid plastic but compressible with volume inconstancy.
- The density distribution is non-uniform throughout the deforming process.
- The yielding is sensitive to hydrostatic stress.
- The deformation is inhomogeneous and barreling is considered.
- Coefficient of friction is constant and both sliding and sticking friction are considered. The friction due to adhesion (sliding friction) has considered as function of relative density \( \rho_r \).
- The forging die-faces are flat and rigid.
- Pressure is normal to the contact-surfaces of the dies.
- Elastic deformation is neglected.

Tabata and Masaki (1978) [9] proposed the following yield criterion:

\[
\rho^k \sigma_o = \sqrt{3I_2^f} \pm 3\eta \sigma_m \tag{1}
\]

(-) sign is for compressive load and \( \eta \leq 0 \). The values of \( \eta \) and \( k \) were determined experimentally:

\[
\eta = 0.54(1 - \rho)^{1.2}, \quad k = 2, \quad \text{for } \sigma_m \leq 0 \tag{2}
\]

For axisymmetric conditions the equation (1), becomes

\[
\sigma_1 = \frac{\rho^k \sigma_o}{(1-2\eta)} + \frac{(1+\eta)}{(1-2\eta)} \sigma_2 \tag{3}
\]

The moment yielding starts the equation reduces to give flow stress as

\[
\lambda = \frac{\rho^k \sigma_o}{(1-2\eta)} \tag{4}
\]

According to Tabata and Masaki (1978) [9] the principal strain increments are given as

\[
d\varepsilon_i = d\lambda \left[ \frac{3(\sigma_1 - \sigma_2)}{2I_2^f} \right] \pm \eta, \quad \text{(for } i = 1, 2, 3 \text{)} \tag{5}
\]

where

\[
d\lambda = \frac{\tau}{\sqrt{3}} \sqrt{(d\varepsilon_1 - d\varepsilon_2)^2 + (d\varepsilon_2 - d\varepsilon_3)^2 + (d\varepsilon_3 - d\varepsilon_1)^2}
\]

a positive constant, the volumetric strain increment \( d\varepsilon_v \) is given as

\[
d\varepsilon_v = d\varepsilon_1 + d\varepsilon_2 + d\varepsilon_3 = \pm 3\eta d\lambda = \pm \mu \sqrt{3} \eta [(d\varepsilon_1 - d\varepsilon_2)(d\varepsilon_2 - d\varepsilon_3) + (d\varepsilon_3 - d\varepsilon_1)] 12 \tag{6}
\]

For axisymmetric compression it yields the compatibility equation as

\[
\varepsilon_r = \frac{(2\eta - 1)}{2(\eta + 1)} \ln \frac{b_2}{b_1} \tag{7}
\]

Frictional condition between deforming tool and work piece in metal forming are of great importance and depends upon various factors discussed by Derygin (1952) [10]. The relative velocity between the work piece materials creates the conditions essential for adhesion in addition to sliding. During plastic deformation of metal powder porous specimen mechanism of composite friction occurs and the shear stress equation becomes

\[
\tau = \mu(p + \rho_0 \phi_0) \tag{8}
\]

Forging of Cylindrical Porous Specimen into Rivet at Different Strain Rates:

Mathematical Analysis:

Figure 1 shows the cylindrical porous specimen in shaped heading process. One end of the cylindrical sintered powder porous specimen is clamped at lower end of the die set. The punch has circular cavity to give the shape of circular rivet of 5 mm head thickness. The punch moves down ward with velocity \( U_o \) and lower platen remains stationary. An upper bound analysis is considered in “near-net” shape dynamic heading at different strain rates.

During the axisymmetric shaped heading process, the porous specimen is subdivided into two zones of deformation. In zone 1, the case is similar to the axisymmetric forging of cylindrical porous specimen between two flat platens at different strain rates and the bulged profiles of the compressed porous specimens were observed as shown in figure 2. Form the traced profile of compressed porous specimen, velocity field was ascertained which was similar to the velocity field chosen by Chitkara and Bhutta (2001) [3].
Velocity fields and Strain rates:-

$$U_z = -\frac{2U_0Z}{3a} + \frac{U_0Z^2}{3a^2} \left( 2 - \frac{Z^2}{a^2} \right)$$  \hspace{1cm} (9)

$$U_\theta = 0$$  \hspace{1cm} (10)

$$U_r = K \left[ \frac{U_0}{3a} + \frac{2U_0Zr}{3a^2} \left( 1 - \frac{Z^2}{a^2} \right) \right]$$  \hspace{1cm} (11)

Strain rates:

$$\dot{\varepsilon}_r = \frac{\partial U_r}{\partial r} = K \left[ \frac{U_0}{3a} + \frac{2U_0Zr}{3a^2} \left( 1 - \frac{Z^2}{a^2} \right) \right]$$  \hspace{1cm} (12)

$$\dot{\varepsilon}_\theta = \frac{U_0}{r} + \frac{1}{r} \frac{\partial U_0}{\partial \theta} = K \frac{U_0}{3a} + \frac{2U_0Z}{3a^2} \left( 1 - \frac{Z^2}{a^2} \right) = \dot{\varepsilon}_r$$  \hspace{1cm} (13)

$$\dot{\varepsilon}_z = -2 \frac{U_0}{3a} + \frac{2U_0Z}{3a^2} \left[ 1 - \frac{Z^2}{a^2} \right]$$  \hspace{1cm} (14)

The value of K is determined by using Tabata & Masaki (1978) [9] compressibility equation

$$\dot{\varepsilon}_r + \dot{\varepsilon}_\theta + \dot{\varepsilon}_z = \pm 2\eta \sqrt{(\dot{\varepsilon}_r - \dot{\varepsilon}_\theta)^2 + (\dot{\varepsilon}_\theta - \dot{\varepsilon}_z)^2 + (\dot{\varepsilon}_z - \dot{\varepsilon}_r)^2}$$  \hspace{1cm} (15)

substituting the strain rates in compressibility equation (15) and solving for compressive load condition, gives

$$K = \frac{(1-2\eta)}{(1+\eta)}$$  \hspace{1cm} (16)

Internal power of deformation ($W_i$):

$$W_i = \frac{2}{\sqrt{3}} \sigma_0^0 \int \sqrt{\frac{1}{2} \varepsilon_{ij} \varepsilon_{ij}} \cdot dv = 2\pi r dr dz$$  \hspace{1cm} (17)

$$W_i = \frac{2\pi \sqrt{2}}{\sqrt{3}} \sigma_0^0 \int \left( \dot{\varepsilon}_r^2 + \dot{\varepsilon}_\theta^2 + \dot{\varepsilon}_z^2 \right) r dr dz$$

substituting the value of strain rates

$$W_i = \frac{4\pi \sqrt{(K^2 + 2)}}{\sqrt{3}} \sigma_0^0 \int_{r=0}^{r_0} \left[ \frac{2U_0}{3a} + \frac{8U_0Z}{3a^2} \left( 1 - \frac{4Z^2}{a^2} \right) \right] r dr dz$$

$$= \frac{\sqrt{(K^2 + 2)}}{\sqrt{3}} \left( \pi r_0^2 \right) \sigma_0^0 U_0$$  \hspace{1cm} (18)

Energy dissipation due to Velocity discontinuity ($W_v$):-

At $Z= a$ (top) surfaces the velocity discontinuity is

$$|\Delta V| = K \left[ \frac{U_0r}{3a} \right]$$  \hspace{1cm} (19)

$$W_v = 2\pi \sigma_0^0 \int_0^{r_0} |\Delta V| r dr$$

$$W_v = \frac{2\pi \eta \sigma_0^0 U_0 K}{9a}$$  \hspace{1cm} (20)

Frictional power losses ($W_f$):-

Both at top and bottom surfaces $Z=0$ & $Z= a$, the velocity discontinuity is: $|\Delta V| = K \left[ \frac{U_0r}{3a} \right]$

The energy dissipation rate due to friction at the tool metal interfaces is given by

$$W_{f1} = 2\pi \left[ \int_0^{r_{ex}} K \left[ \frac{U_0r}{3a} \right] \tau |\Delta U| dr \right]$$

$$W_{f1} + W_{f2}$$  \hspace{1cm} (21)

$r_{ex}$ is new expanded radius of the specimen. Considering composite friction, the sticking zone lies at
the centre and in its vicinity and rest of the outer area of contact surface is a sliding zone. The shear stress as given by Rooks (1974) [11]

\[
\tau = \mu \left[ \bar{p} + \rho_0 \phi_0 \left( 1 - \frac{r_m - r}{r_m - r_0} \right) \right] \tag{22}
\]

Sticking radius \( r_m = r - \left( \frac{h}{2\mu} \right) \ln \frac{1}{\sqrt{3}\mu} \) and \( n > n \) is a constant, \( n >> 1 \).

At top surface of the rivet head, i.e. \( z = a, r = 0 \) to \( r = r_e \)

\[
W_{ft1} = 2\pi \int_0^{r_e} \mu K \left[ \bar{p} + \rho_0 \phi_0 \left( 1 - \frac{r_m - r}{r_m - r_0} \right) \right] r dr
\]

Putting \( \rho_0 \phi_0 = x, p \) & integrating

\[
W_{ft1} = \left( \frac{2\pi \rho K U_0}{3a} \right) \left[ \frac{r_e^3}{3} + \frac{x r_e^3}{3} - \frac{x r_m r_e^3}{3n r_0} + \frac{x r_m}{r} \right] \tag{23}
\]

Similarly at bottom surface of rivet head i.e. \( z = a, r = r_e \) to \( r = r_0 \)

\[
W_{ft2} = \left( \frac{2\pi \rho K U_0}{3a} \right) \left[ \frac{r_m^3}{3} + \frac{x (r_m^3 - r_0^3)}{3} - \frac{x (r_m^3 - r_e^3)}{3} \right] \tag{24}
\]

\[
W_{ft} = \left( \frac{2\pi \rho x^3}{3a} \right) \left[ \frac{1 + x - x r_m}{3} \right] \left[ \frac{r_e^3}{3} - \frac{r_m^3}{3} \right] + \frac{x (r_e^3 - r_0^3)}{3} \tag{25}
\]

Energy dissipation due to Inertia \( W_a \):

\[
W_a = \rho_p \int U_t U_t dv \tag{24}
\]

\( \rho_p \) - specimen density. The equation in expanded form

\[
W_a = 2\pi \rho_p \int_0^{r_0} \left\{ U_t U_t + U_0 U_0 + U_z U_z \right\} r dr dz
\]

The acceleration-components \( U_t, U_0, \) and \( U_z \) in the cylindrical coordinate system \((r, \theta, z)\) are:

\[
U_t = \frac{\partial U_t}{\partial t} + U_r \frac{\partial U_t}{\partial r} + \frac{U_0}{r} \frac{\partial U_t}{\partial \theta} + U_z \frac{\partial U_t}{\partial z} - \frac{U_0^2}{r}
\]

\[
U_z = \frac{\partial U_z}{\partial t} + U_r \frac{\partial U_z}{\partial r} + \frac{U_0}{r} \frac{\partial U_z}{\partial \theta} + U_z \frac{\partial U_z}{\partial z} - \frac{U_0 U_z}{r}
\]

Substituting the values

\[
U_0 = 0 \tag{25}
\]

\[
U_t = K \left[ \frac{r}{3a} + \frac{Z}{a} \left( 1 - \frac{Z^2}{a^2} \right) \right] \left[ \dot{U} - K U_0 \left( \frac{1}{3a} + \frac{Z}{a} \right) \left( 1 - \frac{Z^2}{a^2} \right) \right] \tag{26}
\]

\[
U_z = - \left[ \dot{U} - U_0 \left( \frac{2}{3a} + \frac{4Z}{3a} - \frac{3Z^2}{3a^2} \right) \right] \tag{27}
\]

Substituting the velocity and acceleration components in equation (24) and after integration

\[
W_a = 2\pi \rho \int_0^{r_0} \left\{ U_t \left\{ 0.213 K^2 \left( \frac{1}{a} \right)^2 + 0.167 \right\} \right. + U_0 0.0439 K 2 \rho a^2 + K 4 + 0.056 \tag{28}
\]

External power supplied by the press:

During deformation the external powder \( J^* \) supplied by the ram

\[
J^* = W_t + W_v + W_i + W_a + W_t \tag{29}
\]

The last term \( (W_t) \) is power supplied by predetermined body tractions and since there is no surface traction so the value of \( W_t \) is considered as zero. Therefore,

\[
J^* = \int F_t U_0 ds = PU_0 = U_0 \int_0^{r_0} 2\pi \bar{p} dr = \pi r_0^2 \bar{p} U_0 \tag{30}
\]

\( \bar{p} \) is average pressure on the specimen’s forging face.

Relative Average Forging Pressure:-

\[
J^* = \int F_t U_0 ds = \pi r_0^2 \bar{p} U_0 = W_t + W_v + W_i + W_a \tag{31}
\]

Substituting the values of \( W_t, W_v, W_i, \) & \( W_a \) in equation (31), the relative average forging pressure on the platen:
III. MATERIALS AND METHOD

The aluminum metal powder “Qualikem” make was compacted at a compaction pressure of 300 Mpa in a closed circular cavity of diameter 20 mm on 400 kN computerized UTM to fabricate the green compacts. These compacts were sintered in an endothermic atmosphere at 500 °C for two hours in a muffle furnace. The density of the specimen was obtained simply by measuring dimensions and weight. The specimens had a relative density of 0.9 approximately. The specimen was forged into a rivet by using closed rivet forming die set comprising of four components as shown in figure 3. One end of the specimen was clamped at the lower part of the die set. The punch of 30 mm diameter moves in a die component having cavity of 30 mm plus enclosing the upper part of the clamped specimen. The required travel of the punch is set to form the rivet. Figure 4 shows the arrangement of die components while forging the rivet on the UTM. Approximately 15 mm height of the specimen was used to form the rivet head of 30 mm diameter and 5 mm head thickness. Figures 5 & 6 show the formed rivet form the porous specimen. The forging was done at different strain rates on the UTM. The load with percentage reduction in height was recorded in the excel sheet.

IV. RESULTS AND DISCUSSIONS

The density and modulus of elasticity of aluminum metal were considered as 2.7 gm/cm³ and 70 GPa. The flow stress “σ₀” of the metal was calculated at a strain value of 0.15%.

The parametric results are presented graphically. The variation of the relative average forging pressure versus percentage reduction in height of the porous specimen have been plotted using the equation (32) by changing one of the considered parameters. Figure 7 shows this variation for different values of strain rates. It is observed that for given percentage reduction in height as the strain rate increases the relative average forging pressure also increases. Figure 8 and figure 9 show this variation for different values of coefficient of friction and cohesive friction factor ‘x’ respectively. For considered percentage reduction in height as these values are
increased the relative average forging pressure also increased. In figure 10 shows that with the increase in the value of constant ‘n’ the relative average forging pressure decreases.

Figure 11 shows the variation of the relative average forging pressure versus strain rate at 50 percent height reduction for different values of specimen relative densities. Figure 12 shows the variations of dynamic effect with strain rate for different values of specimen relative densities. For considered strain rate, as the relative density increases the relative average forging pressure and the dynamic effect also increases. As the relative density increases the porosity of the specimen reduces resulting in higher relative average forging pressure.

The experimental results had been plotted as the variation of the relative average forging pressure versus percentage reduction in height, shown in figure 13, for the specimen of relative density 0.9, forged at strain rate 2 mm/sec. The experimental and theoretical results obtained using equation (32), were superimposed for the specimens of relative densities: 0.9, 0.95 and 0.98 and considered values of coefficient of friction 0.3, cohesive factor “x” 0.3 and constant n=3. A close agreement of experimental and theoretical results has been observed. As the forging pressure increases the compressed specimen density also increases, this is evident from the experimental result curve intersecting the theoretical results curves.

Figure 5: Relative average forging pressure versus percentage reduction in height

Figure 6: Relative average forging pressure versus percentage reduction in height

Figure 7: Relative average forging pressure versus percentage reduction in height

Figure 8: Relative average forging pressure versus percentage reduction in height.


V. CONCLUSION

From the limited experiments and theoretical investigations into near-net shaped dynamic heading of circular shaped head form initially cylindrical aluminum porous specimen at different strain rates following conclusions are made:

1. Theoretically determined die load and die movement curves are continuous during the process for selected relative densities of the specimens and also experimentally observed curves are continuous but cutting the theoretical curves of higher relative density of the specimens

2. At different strain rates the specimens of similar relative density and for the same die movement, the die loads are about 20-30 % higher in comparison with at strain rate of 1.5 mm/sec.

3. During sinter forging process, the controlling factors are: strain rate, the amount of interfacial friction between die-work piece interface, the initial density and composition of the specimen.

The correlation between experimental and predicted load values based on the upper bound analysis taking inertia into account is considered reasonably satisfactory for these preliminary investigations. There is a need for some further investigation in the dynamic heading analysis, especially at the corner filling stage for the shapes such as triangular, square, hexagonal etc. to obtain good correlation between analytical predictions and experiments.

Notations

- \( \rho_r \) relative density of the specimen
- \( \varphi_0 \) specific cohesion of the contact surface
- \( \lambda \) flow stress of the metal powder specimen
- \( k \) constant equal to 2
- \( \eta \) function of relative density of specimen
- \( \delta \) a positive constant
- \( P \) die load
- \( p \) pressure
- \( \tau \) shear stress
- \( n \) a constant quantity much greater than unity
- \( \mu \) Coefficient of friction
- \( \sigma_1, \sigma_2, \sigma_3 \) principal stresses
- \( d\varepsilon_1, d\varepsilon_2, d\varepsilon_3 \) principal-strain increments
- \( x, y, z \) Cartesian co-ordinates
- \( r, \theta, z \) Polar co-ordinates
- \( a \) initial height of the specimen
- \( h \) instantaneous thickness of the compressed specimen
\[ \sigma_0 \] yield stress of the composite metal
\[ \sigma_m \] hydrostatic stress
\[ J'_2 \] second invariant of the deviatoric stress
\[ r_m \] radius of the sticking zone

Subscripts

1. Initial condition
2. Final condition

REFERENCES