CHAPTER - 6

ANALYSIS AND DISCUSSION OF RESULTS

In chapters 3 & 4, the methods of analysis and computer programs based on the Finite Difference Method and Finite Element Method, for the analysis of cold forging of sintered powder metal compacts were presented in detail. The results obtained from the analytical model were validated against the experimental observations in chapter 5. In the present chapter, the typical computer results for the stresses and strains produced and densification achieved are presented and discussed to understand the mechanics of cold forging of porous materials under free upsetting.

6.1 DISTORTED MESH

Figs 6.1 to 6.6 depict the distorted mesh for all the three slenderness ratios after 10 and 20 percent reduction in height of the specimens.

6.2 DISTRIBUTION OF STRAIN COMPONENTS

Figs 6.7 to 6.30 show the typical distribution of strain components $\varepsilon_r$, $\varepsilon_\theta$, $\varepsilon_z$ and $\varepsilon_{rz}$ at 10 and 20 percent reduction in height of the specimens. It may be noticed that whereas, $\varepsilon_r$ and $\varepsilon_\theta$ are positive everywhere, $\varepsilon_z$ is negative throughout the workpiece. Further, these strain components increase with the increasing compression ratio. All these strain components are maximum for material elements situated at equatorial plane. Also, the magnitudes of $\varepsilon_r$, $\varepsilon_\theta$ and $\varepsilon_z$ decrease towards the top centre of the workpiece situated near longitudinal axis. Regarding the distribution of shear strain component $\varepsilon_{rz}$ these are mostly negative.
FIG. 6-1 DISTORTED MESH AT 10% DEF. (L/D=0.65)
FIG. 6.2 DISTORTED MESH AT 10% DEF. (L/D = 0.87)
FIG. 6-3 DISTORTED MESH AT 10% DEF. (L/D=1.00)
FIG. 6.4 DISTORTED MESH AT 20% DEF. (L/D = 0.65)
FIG. 6.5 DISTORTED MESH AT 20% DEF. (L/D = 0.87)
FIG. 6.6 DISTORTED MESH AT 20 % DEF (L/D = 1.00)
FIG. 6.7 AXIAL STRAIN DISTRIBUTION AT 10% DEF (L/D=0.65)

FIG. 6.8 RADIAL STRAIN DISTRIBUTION AT 10% DEF (L/D=0.65)
FIG. 6.9 CIRCUMFERENTIAL STRAIN DISTRIBUTION AT 10% DEF. (L/D = 0.65)

FIG. 6.10 SHEAR STRAIN DISTRIBUTION AT 10% DEF. (L/D = 0.65)
FIG. 6.11 AXIAL STRAIN DISTRIBUTION AT 20% DEF. (L/D = 0.65)

FIG. 6.12 SHEAR STRAIN DISTRIBUTION AT 20% DEF. (L/D = 0.65)
FIG. 6.13 RADIAL STRAIN DISTRIBUTION AT 20% DEF. (L/D = 0.65)

FIG. 6.14 CIRCUMFERENTIAL STRAIN DISTRIBUTION AT 20% DEF. (L/D = 0.65)
FIG. 6.15 AXIAL STRAIN DISTRIBUTION AT 10% DEF. (L/D = 0.87)

FIG. 6.16 RADIAL STRAIN DISTRIBUTION AT 10% DEF. (L/D = 0.87)
FIG. 6-17 CIRCUMFERENTIAL STRAIN DISTRIBUTION AT 10% DEF. (L/D = 0.97)

FIG. 6-18 SHEAR STRAIN DISTRIBUTION AT 10% DEF. (L/D = 0.87)
FIG. 6.19 AXIAL STRAIN DISTRIBUTION AT 20% DEF. (L/D=0.87)

FIG. 6.20 RADIAL STRAIN DISTRIBUTION AT 20% DEF. (L/D=0.87)
FIG. 6.21 CIRCUMFERENTIAL STRAIN DISTRIBUTION AT 20% DEF. (L/D = 0.87)

FIG. 6.22 SHEAR STRAIN DISTRIBUTION AT 20% DEF. (L/D = 0.87)
FIG. 6.23 AXIAL STRAIN DISTRIBUTION AT 10% DEF. (L/D=1.00)
FIG. 6.24 RADIAL STRAIN DISTRIBUTION AT 10% DEF. (L/D=1.00)
FIG. 6.25 CIRCUMFERENTIAL STRAIN DISTRIBUTION AT 10% DEF. (L/D = 1.00)
Fig. 6-26 SHEAR STRAIN DISTRIBUTION AT 10% DEF. (L/D=1.00)
FIG. 6.27 AXIAL STRAIN DISTRIBUTION AT 20% DEF. (L/D = 1.00)

FIG. 6.28 RADIAL STRAIN DISTRIBUTION AT 20% DEF. (L/D = 1.00)
FIG. 6.29  CIRCUMFERENTIAL STRAIN DISTRIBUTION AT 20% DEF. (L/D = 100)

FIG. 6.30  SHEAR STRAIN DISTRIBUTION AT 20% DEF. (L/D = 1.00)
and decreasingly, become zero at the free surface near equatorial plane for higher level of percentage deformation (20%) in height for the slenderness ratios of 0.87 and 1.00. However, for the specimens of slenderness ratios of 0.65 and 0.87, at 20 percent reduction in specimen height, the shear strain also becomes zero near the centre of workpiece at the equatorial plane. Shear strains in general are largest at the top face near the corner of the workpiece and decrease towards equatorial plane.

6.3 DISTRIBUTION OF STRESS COMPONENTS

Figs 6.31 to 6.54 show the typical distribution of $\sigma_z$, $\sigma_r$, $\sigma_0$ and $\sigma_{rz}$ in the workpiece after 10 and 20 percent reduction in specimen height. It may be noticed that $\sigma_z$ remains compressive (negative value being taken as compressive) everywhere for the specimens of all the three slenderness ratios. The maximum value of $\sigma_z$ occurs towards the centre of the workpiece near the longitudinal axis and decreases towards the free surface particularly near the equatorial plane.

$\sigma_r$ remains compressive almost in the entire workpiece and decreasingly becomes zero at the free surface near the equatorial plane. The maximum value of $\sigma_r$ occurs at the top face near the longitudinal axis.

$\sigma_0$ also varies in a manner very similar to $\sigma_r$. However, at the free surface near the equatorial plane, the $\sigma_0$ values become tensile in nature for the specimens of all the three slenderness ratio both at 10 percent and 20 percent deformation in specimen height.

Next, the shear stress $\sigma_{rz}$ also remains largely compressive in the centre as
FIG. 6.31 AXIAL STRESS DISTRIBUTION AT 10% DEF. (L/D=0.65) MPa

FIG. 6.32 SHEAR STRESS DISTRIBUTION AT 10% DEF. (L/D=0.65) MPa
FIG. 6-33 RADIAL STRESS DISTRIBUTION AT 10% DEF. (L/D = 0.65) MPa

FIG. 6-34 CIRCUMFERENTIAL STRESS DISTRIBUTION AT 10% DEF. (L/D = 0.65) MPa
FIG. 6.35 AXIAL STRESS DISTRIBUTION AT 20\% DEF. (L/D=0.65) MPa.

FIG.6.36 SHEAR STRESS DISTRIBUTION AT 20\% DEF. (L/D=0.65) MPa.
FIG. 6.37 RADIAL STRESS DISTRIBUTION AT 20% DEF. (L/D=0.65) MPa

FIG. 6.38 CIRCUMFERENTIAL STRESS DISTRIBUTION AT 20% DEF. (L/D=0.65) MPa
FIG. 6.39 AXIAL STRESS DISTRIBUTION AT 10% DEF. (L/D=0.87) MPa

FIG. 6.40 SHEAR STRESS DISTRIBUTION AT 10% DEF. (L/D=0.87) MPa
FIG. 6.41 RADIAL STRESS DISTRIBUTION AT 10% DEF. (L/D=0.87) MPa

FIG. 6.42 CIRCUMFERENTIAL STRESS DISTRIBUTION AT 10% DEF. (L/D=0.87) MPa
FIG. 6.43 AXIAL STRESS DISTRIBUTION AT 20% DEF. (L/D = 0.87) MPa

FIG. 6.44 RADIAL STRESS DISTRIBUTION AT 20% DEF. (L/D = 0.87) MPa
FIG. 6.45 CIRCUMFERENTIAL STRESS DISTRIBUTION AT 20% DEF. (L/D = 0.87) MPa

FIG. 6.46 SHEAR STRESS DISTRIBUTION AT 20% DEF. (L/D = 0.87) MPa
FIG. 6.47 AXIAL STRESS DISTRIBUTION AT 10% DEF. (L/D = 1.00) MPa
FIG. 6.48  RADIAL STRESS DISTRIBUTION AT 10% DEF. (L/D=100) MPa
FIG. 6.49  CIRCUMFERENTIAL STRESS DISTRIBUTION AT 10% DEF. (L/D = 1.00) MPa
FIG. 6.50 SHEAR STRESS DISTRIBUTION AT 10% DEF. (L/D=W) MPa
FIG. 6.51 AXIAL STRESS DISTRIBUTION AT 20% DEF. (L/D=100) MPa

FIG. 6.52 RADIAL STRESS DISTRIBUTION AT 20% DEF. (L/D=100) MPa
FIG. 6.53  CIRCUMFERENTIAL STRESS DISTRIBUTION AT 20% DEF. (L/D=100) MPa

FIG. 6.54  SHEAR STRESS DISTRIBUTION AT 20% DEF. (L/D=100) MPa
well as top portion of the workpiece. The largest value of $\sigma_{x}$ is observed at the top surface near the corner of the workpiece. This value progressively decreases towards the equatorial plane and eventually becomes zero at the centre of workpiece on the equatorial plane and at the free surface.

6.4 DISTRIBUTION OF EFFECTIVE PLASTIC STRAIN AND EFFECTIVE STRESS

The effective plastic strain and the effective stress associated with any element are indicative of the degree of deformation of that element. The effective plastic strain and effective stress have been computed using equation (2.13) and (2.4) respectively. Figs 6.55 to 6.66 show the distribution of effective plastic strain and effective stress throughout the body of deformed workpiece after 10 and 20 percent reduction in specimen height. It may be noticed that maximum of both $\varepsilon_p$ and $\sigma$ occurs at the centre of workpiece and near the equatorial plane. Values of effective stress however decrease towards the free surface of the workpiece achieving a minimum at the free surface close to equatorial plane. The values of effective plastic strain achieve a minimum at the top face near the longitudinal axis of the workpiece. With increasing compression, magnitudes of both $\varepsilon_p$ and $\sigma$ for all the material elements go on increasing. However, the nature of distribution remains unaltered.

6.5 DISTRIBUTION OF RELATIVE DENSITY

Figs 6.67 to 6.72 show the distributions of relative density developed in the body of workpiece after 10 and 20 percent reduction in height of the specimens. It may be noticed that significant densification occurs near the centre of workpiece
FIG. 6.55  EFFECTIVE PLASTIC STRAIN DISTRIBUTION AT 10% DEF. (L/D=0.65)

FIG. 6.56  EFFECTIVE STRESS DISTRIBUTION AT 10% DEF. (L/D=0.65) (COMP) MPa
FIG. 6.57  EFFECTIVE PLASTIC STRAIN DISTRIBUTION AT 20% DEF. (L/D = 0.65)

FIG. 6.58  EFFECTIVE STRESS DISTRIBUTION AT 20% DEF. (L/D = 0.65) (COMP.) MPa
FIG. 6.59 EFF. PLASTIC STRAIN DISTRIBUTION AT 10% DEF. (L/D=0.87)

FIG. 6.60 EFFECTIVE STRESS DISTRIBUTION AT 10% DEF. (L/D=0.87) (COMP) MPa
FIG. 6.61  EFFECTIVE STRESS DISTRIBUTION AT 20% DEF. (L/D=0.87) (COMP.) MPa

FIG. 6.62  EFFECTIVE PLASTIC STRAIN AT 20% DEF. (L/D=0.87)
FIG. 6-63 EFFETIVE PLASTIC STRAIN DISTRIBUTION AT 10% DEF. (L/D=1.00)
FIG. 6-64 EFFECTIVE STRESS DISTRIBUTION AT 10% DEF. (L/D = 100)(COMP) MRₐ
FIG. 6-65 EFFECTIVE PLASTIC STRAIN AT 20% DEF. (L/D = 1000)
FIG. 6.66 EFFECTIVE STRESS DISTRIBUTION AT 20% DEF. (L/D=10)(COMP)M_{Rk}
FIG. 6-67 RELATIVE DENSITY DISTRIBUTION AT 10% DEF. (L/D = 0.65)

FIG. 6-68 RELATIVE DENSITY DISTRIBUTION AT 20% DEF. (L/D = 0.65)
FIG. 6.69 RELATIVE DENSITY DISTRIBUTION AT 10% DEF. (L/D = 0.87)

FIG. 6.70 RELATIVE DENSITY DISTRIBUTION AT 20% DEF. (L/D = 0.87)
FIG. S.71 RELATIVE DENSITY DISTRIBUTION AT 10%DEF (L/D=1.00)
FIG. 6.72 RELATIVE DENSITY DISTRIBUTION AT 20% DEF. (L/D = 1.00)
and on the corners of the workpiece body. The relative density goes on increasing with the increasing compression ratio. The portion in the centre of quarter of the workpiece is having least density. Relative density is particularly less at the free surface close to equatorial plane. Maximum relative density is observed near the centre of the workpiece.

Densification of forged workpieces after 20 percent reduction in specimen height was also studied with the help of metallurgical microscope (magnification 300X). The specimens were cut into two halves and the surface was made to mirror finish. The right hand top quarter portion of all the specimens with different slenderness ratios was observed under the metallurgical microscope. The complete portion was scanned and photomicrographs were taken. A qualitative presentation on the void shape and decay can be examined in plates 1 to 12 with reference to fig. 6.73. It can be observed in these plates that the voids are fine in zones II & III which are more dense zones as compared to large voids observed in the zones I & IV which are relatively less dense.

6.6 EXPLANATION OF THEORETICAL RESULTS

In the current section, an attempt has been made to present a plausible explanation of theoretical results described in the earlier sections. It may be observed that material elements that are in contact with press platens, experience a frictional resistance, undergo a negligible movement in the radial direction. However, the material elements at the top face undergo a considerable movement in vertically downward direction. On the other hand, due to symmetry about the equatorial plane, the vertical displacement vanishes at the equatorial plane. Thus, the material elements near the equatorial plane, move more or less radially outwards. Thus the flow pattern has to undergo a transition from a vertically
FIG. 6-73 LOCATION OF ZONES FOR PLATES
PLATE 1 Photomicrograph of Pores at 20% Deformation (L/D=0.65, Zone-1)

PLATE 2 Photomicrograph of Pores at 20% Deformation (L/D=0.65, Zone-2)
PLATE 3 Photomicrograph of Pores at 20% Deformation (L/D=0.65, Zone-3)

PLATE 4 Photomicrograph of Pores at 20% Deformation (L/D=0.65, Zone-4)
PLATE 5 Photomicrograph of Pores at 20% Deformation (L/D=0.87, Zone-1)

PLATE 6 Photomicrograph of Pores at 20% Deformation (L/D=0.87, Zone-2)
PLATE 7 Photomicrograph of Pores at 20% Deformation (L/D=0.87, Zone-3)

PLATE 8 Photomicrograph of Pores at 20% Deformation (L/D=0.87, Zone-4)
PLATE 9  Photomicrograph of Pores at 20% Deformation (L/D=1.00, Zone-1)

PLATE 10  Photomicrograph of Pores at 20% Deformation (L/D=1.00, Zone-2)
PLATE 11 Photomicrograph of Pores at 20% Deformation (L/D=1.00, Zone-3)

PLATE 12 Photomicrograph of Pores at 20% Deformation (L/D=1.00, Zone-4)
downward motion to a radially outward motion as we move from top face to equatorial plane. The nature of flow pattern has been shown in fig. 6.74. At larger deformations, however, elements situated near the top face undergo a greater radial movement, particularly for the specimens with lesser slenderness ratio. This radial movement is least near the longitudinal axis and gradually increases as we move away from the longitudinal axis towards the edge of the workpiece. However, the flow pattern near the equatorial plane remains unaltered. This behaviour can be justified on account of the fact that for lesser slenderness ratio, at higher level of percentage reduction in height the discrepancy between experimental load and predicted load is also greater.

The distribution of strain components is obviously influenced by the flow pattern of material elements. As can be seen, the radial and circumferential strain components $\varepsilon_r$ and $\varepsilon_0$ are smaller near the top face and particularly near the longitudinal axis. The axial strain component $\varepsilon_z$ also varies in the similar manner but the ratio of minimum and maximum axial strain is comparatively low as compared to minimum and maximum radial or circumferential strain. This is due to the fact that material has some compressibility. The strain components at the top face and near the outer boundary are larger in magnitude than at smaller radii due to sharp gradients in radial & axial displacements. However, there is a transformation in this variation of strain components at the equatorial plane and strain components at smaller radii become larger in magnitude as compared to the ones at larger radii. The reason is that material elements at larger radii experience
FIG. 6-74. FLOW-PATTERN AT 20% COMPRESSION
a larger radial movement as compared to the material portion near the small radii at
the equatorial plane.

Further, for the shear strains, which are given by \( \varepsilon_{zz} = \frac{1}{2} \left( \frac{\partial \Delta u}{\partial z} + \frac{\partial \Delta w}{\partial r} \right) \), it can be observed that the magnitude of \( \frac{\partial \Delta u}{\partial z} \) is maximum at the top face and reduces to zero at equatorial plane. On the other hand, \( \frac{\partial \Delta w}{\partial r} \) is zero both at top face and equatorial plane. From this, therefore, we conclude that the shearing strains are maximum at the top face and gradually reduce to zero near the centre of specimen and at free surface at equatorial plane. The shear stress \( \sigma_{zz} \), which is proportional to the shear strain, too has distribution quite similar to shear strain (Figs. 6.7 to 6.31)

Coming to the distribution of radial stress component, \( \sigma_r \) we refer to the equilibrium equation in the radial direction which is given as:

\[
\frac{\partial \sigma_r}{\sigma_r} + \frac{\partial \sigma_z}{\sigma_z} + \frac{\sigma_r - \sigma_\theta}{\rho} = 0
\]

The contribution of third term on the left is almost negligible particularly near the longitudinal axis. As already discussed \( \frac{\partial \sigma_r}{\partial z} \) is negative and \( \frac{\partial \sigma_z}{\partial r} \) is positive. Together with the fact that \( \sigma_r \) is nearly zero at the free surfaces it can be observed that \( \sigma_r \) goes on decreasing (increasing in the compressive sense) as we proceed from the free surface towards the longitudinal axis. Further, as the value of \( \frac{\partial \sigma_r}{\partial z} \) decreases towards the equatorial plane, the radial stresses, accordingly
decrease in magnitude near the centre of specimen at equatorial plane, compared to radial stress near top centre on the longitudinal axis.

The distribution of circumferential stress $\sigma_\theta$ is also largely compressive and too varies in a manner quite similar to radial stress $\sigma_r$. The combined effect of variation of $\sigma_r$ and $\sigma_z$ with 'r'; and $\sigma_\theta$ is, that $\sigma_\theta$ decreases from a compressive value less rapidly with 'r' near the top face and more rapidly near the equatorial plane and ultimately becoming tensile in nature at free surface on the equatorial plane (Figs. 6.32 to 6.56).

The distribution of axial stress $\sigma_z$ is explained in the following manner. The value of axial strain is largest at the centre of equatorial plane. As $\varepsilon_r$ and $\varepsilon_\theta$ are also largest in this region, a maximum value of $\sigma_z$ is expected at this region. The value of $\sigma_z$ decreases as we move outwards along the equatorial plane, since $\varepsilon_z$ also decreases there in radial direction. (Figs. 6.32 to 6.56). Coming to the top face, magnitude of $\varepsilon_z$ is smallest at the centre and increases towards the periphery. But due to the presence of high radial and circumferential stresses in this region the value of $\sigma_z$ near the longitudinal axis is more and gradually reduces with increasing ‘r’ up to a certain material element before the top corner. It may be noted in the plots of radial stress distributions that a kink is produced in the material element before the top most corner. The net effect of this kink is in an increased $\sigma_z$ and $\sigma_\theta$ value in the top most corner material element.

The distribution of effective plastic strain $\varepsilon_p$ and the effective stress $\bar{\sigma}$ will be the same as the strain components. Therefore, $\varepsilon_p$ and $\bar{\sigma}$ will also be
maximum at the centre of equatorial plane as can be confirmed from figs. 6.55 to 6.66. The magnitude of $\bar{\sigma}$ gradually reduces as we move towards free surface. However, there are two critical zones $\left( \frac{\bar{\sigma}}{\sigma_i} > 1 \right)$ (i) one at the centre on the equatorial plane and (ii) second one at the top right corner. As the ratio of compression goes on increasing, the critical zones will go on expanding and non-critical zones will go on shrinking. The material elements within the critical zone will achieve a higher and higher level of relative density as compared to material elements under non-critical zone. The distribution of effective plastic strain has also been shown in figs 6.55 to 6.66. This distribution is also similar to the distribution of strain components shown earlier.

6.7 EFFECT OF SLENDERNESS RATIO

It maybe recalled that variation of forging load and the bulge developed at the free surface with respect to increase in percentage reduction in specimen height for different slenderness ratios were presented in section 5.5. From the results presented the effect of slenderness ratio on the forging load and the bulge at free surface, for the same percentage reduction in height of the specimen can be noticed. Figs. 5.3 to 5.5 show the variation of forging load at various percentage reductions in height for different slenderness ratios. It can be observed that the forging load increases with decrease in slenderness ratio. (for same initial diameter). This behaviour can be explained as given below.

It is well known that for a given frictional condition at the top face, the constraining effect of the frictional stress is largely concentrated over a finite
distance downward from the top face. Therefore, for a specimen of small slenderness ratio, the boundaries of the restraining region will extend deeper into the specimen as compared to the specimens of higher slenderness ratios. The effect of this restraining factor is to increase the inhomogeneity of deformation. The inhomogeneity of deformation increases with decrease of slenderness ratio of the specimen. Thus, the total work done by the press platen on the work material comprises of three factors (i) work done for homogeneous deformation i.e. useful work, (ii) frictional work at the top face and (iii) the redundant work which is directly proportional to the level of inhomogeneity. As the redundant work goes on increasing with decrease in slenderness ratio of the specimen, the average effective stress levels in the specimen go on increasing. Hence the forging loads are larger when forging shorter specimens.

Next, an explanation is made to understand the effect of slenderness ratio on the bulge of a specimen, which is defined as the ratio of maximum radius at equatorial plane to minimum radius at the top face of the specimen concerned. As already discussed that shear stresses induced in a shorter specimen as a result of the constraining effects at the top face are larger. As a result, the slope of bulge profiles is more convex at the top. Thus, at a given percentage reduction in height, the increase in volume near the top is greater in shorter specimen. The reverse is true near the equatorial plane. Therefore, the ratio between maximum radius at equatorial plane and minimum radius at the top is smaller for shorter specimens and vice versa. This is confirmed by results predicted by analytical model shown in figs. 5.6 to 5.8.