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Flash-less Cold Forging of Cup-shaped Object and Stress Analysis of Forging Die using FEM Simulation and Experiment

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ABSTRACT

In this paper, computer- aided finite element analysis for flash-less cold forging of cup shaped article is presented. The work-piece specifications are calculated by developing mathematical relations between volumes of die cavity and work-piece. The three dimensional FE simulation is made by DEFORM F3 V 6.0 and geometrical modeling for the die and the work-piece is performed by SOLIDWORKS 2007 4.0. The work-piece used is of AISI 1045 steel and the die material is die steel (AISI D2). The aspect ratios of work-piece for cup shaped article are optimized to obtain minimum flash volume with no under-filling. The stress distribution and deformation in die and the punch is studied to enhance the die life. Among the three types of work-piece geometries (models I, II, III and IV), model IV is found to be the optimum. The results of numerical simulation and analytical calculations are found in satisfactory agreement with the experimental results.

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INTRODUCTION

Forging is a manufacturing process in which metal is pressed, pounded or squeezed under great pressure into high strength parts known as forgings. The process is normally (but not always) performed hot by preheating the metal to a desired temperature before it is worked. Unlike casting process, metal used to make forged parts is never melted and poured. In the area of cold forging die design and optimization, substantial investigations have been carried out by many researchers using various tools and techniques such as finite element method (FEM) artificial neural network (ANN), genetic algorithm (GA) and other computer-aided design (CAD) techniques. The works related to the current study are reviewed and presented here.

Castro *et al*. (2004) made an attempt to obtain optimal design in forging using genetic algorithm. The design problem was formulated as an inverse problem incorporating a finite element thermal analysis model and an optimization technique conducted on the basis of an evolutionary strategy. A rigid viscoplastic flow-type formulation was adopted, valid for both hot and cold processes. The chosen design variables were work-piece preform shape and work-piece temperature. The process design for closed-die forging of a bevel gear used in automobile transmission system was made by Song and Im (2007) using three-dimensional FE simulations. Process variables were the pressing type, punch location, and billet diameter. Based on the simulation results, appropriate process design without causing under-filling and folding defect was determined.

Kim *et al*. (2003) used rigid–plastic finite element simulation to analyze the deformation characteristic of the whole impeller hub forming processes and to optimize the process. Ohashi *et al*. (2003)) developed a computer aided design (CAD) system to design forging sequences and die profiles by considering forging as a procedure for adding features to a raw material, process planning as the inverse procedure, and each step of the forging process as a combination of feature eliminating processes. The system designed the forging sequences and die profiles from the product to its raw material by eliminating features. Hussain *et al*. (2002) presented numerical study on the forming of a clutch-hub using CAD simulation tool CAMPform. Simulations for S10C steel using various die and work-piece geometries were carried out to determine the most suitable forming

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condition for production of the clutch-hub. Ishikawa *et al.* (2000)studied analytically the effects of forming stresses and generated heat on the dimensional change of punch die and work piece during forging. Im *et al.* (1999) introduced a process design technique, based on a forging simulator and commercial CAD software together with its related design system for the cold-former forging of ball joints. Khaleed *et al.*2011, Khaleed *et al.*2010 and Khaleed *et al.* 2012 worked on cold forging and volumetric analysis for different component using Finite Element Method.

Xu and Rao(1997)carried out an analysis of isothermal axisymmetric spike- forging using an integrated FEM code. Influence of different geometric parameters, processing variables and interfacial conditions on the instantaneous spike height were studied. Hsu and Lee(1997) proposed ANN based cold forging process design method suitable for shop floor to decide the cold forging process parameters for producing a sound product within the required minimum quantity of the die set. A computer-aided system called "FORMING" for designing the forming sequence for multistage forging of round parts was presented by Badawy *et al.* (1985). Natsume *et al.*(1989) performed experimental and FEM studies to understand the dimensional difference between forging tools and forged components. Lee *et al.* (2002) evaluated the characteristics of elastic deformation at a forming tool for a cold forged alloyed steel by experimental and FEM analysis. Qin *et al.* (2000) worked to combine coupled thermo-mechanical FE plastic simulation and heat transfer analysis to define heat-flux-density functions across die/work piece interfaces. Flash-less cold forging of an aluminium connecting rod is studied by Vazquez and Altan (2000) using DEFORM-FEM package.

However, the possibility of under-filling in flash-less forging compared with that with flash was not fully investigated. Load calculations for the optimized work-piece (with no under-filling) by means of a 3D FEM simulation, and detailed volumetric analysis of the work-piece are also lacking. These issues are specifically addressed in the current study in which cup-shaped article is formed by cold forging. The work-piece used is of AISI 1045 steel and the die material is die steel (AISI D2). The three dimensional FE simulation is made by DEFORM F3 V 6.0 and geometrical modeling for the die and the work-piece is performed by SOLIDWORKS 2007 4.0. Three work-piece geometries, model I, model II, model III and model IV are tested. The aspect ratios for the all three models are optimized to obtain minimum flash volume with no under-filling. The stress analysis is carried out to study the stress distribution in the die and the punch, and the deformation in the punch is computed.

Methodology:

Finite element formulation:

In cold forging large deformation occurs hence elastic deformation can be neglected and the material is considered as rigid plastic. In this study the rigid-plastic finite element method is applied for analysis of deformation.

The basic equations of the rigid–plastic finite element are as follows Kim(2003):

Equilibrium equation:

$$\sigma_{ij,j}=0 \quad (1)$$

Compatibility and incompressibility condition:

$$\dot{\varepsilon}_{ij=}\frac{1}{2}(u_{ij}+u_{ij}). \quad \varepsilon =\dot{} u_{ij} = 0 \quad (2)$$

Constitutive equations:

$$\sigma'_{ij}=\frac{2\bar{\sigma}}{3\dot{\varepsilon}}\dot{\varepsilon}_{ij}.\bar{\sigma} = \sqrt{\frac{3}{2}}(\sigma'_{ij}\sigma'_{ij}). \quad \dot{\bar{\varepsilon}} = \sqrt{\frac{3}{2}}(\dot{\varepsilon}_{ij}\dot{\varepsilon}_{ij}) \quad (3)$$

Boundary conditions:

$$\sigma_{ij}n_i=F_j \text{ on } S_F,\ u_i=U_i \text{ on } S_U \quad (4)$$

Where σ_{ij} and $\dot{\varepsilon}_{ij}$ are the stress and the strain velocity, respectively. $\bar{\sigma}$ and $\dot{\bar{\varepsilon}}$ are the effective stress and the effective strain velocity, respectively. F_j denotes the force on the boundary surface of S_F and U_i denotes the deformation velocity on the boundary surface of S_U.

The basic mathematical equations are as follows Im(2007):

$$\pi = \int \bar{\sigma}\,\dot{\bar{\varepsilon}}dV - \int_S FiUidS \quad (5)$$

where Π is functional for rigid-plastic material,$\bar{\sigma}$ is the effective stress, $\dot{\bar{\varepsilon}}$ is effective strain rate, Fiis the traction specified on the boundary, s, Uiis the velocity component.

$$\delta\pi = \int_v \bar{\sigma}\delta\dot{\bar{\varepsilon}}\,dV - \int_S FiUidS + \int_V \dot{\varepsilon}_v\,\delta\dot{\varepsilon}_v dV = 0 \quad (6)$$

$\int plstic\ work$- $\int external\ force$ +$large\ penalty\ constant \int change\ volume$.

By introducing the penalty constant K and modifying the functional equation (Eq (6)) the incompressibility constraint on admissible velocity fields may be removed.$\delta\dot{\epsilon}_{v}$ is the arbitrary variation and $\delta\dot{\bar{\varepsilon}}$ and $\delta\dot{\varepsilon}_v$ are variations in strain rate from δU_i **.** Equation (6) can be converted to non linear algebraic equation by using finite element descritization. Using numerical technique like newton-raphson, the solution for nonlinear simultaneous equations can be obtained. In this study deform F3 is used for metal forming simulation and for stress analysis.

Hardness test:

The hardness of the work-piece and forged part is tested to study the effect of forging on hardness. Figure 1 and Figure 2 show the numbered surfaces of forged and unforged parts in hardness testing. From table.1 it is observed that vicker's hardness is increased in the forged part compared to unforged part. The vicker's hardnesses on the surfaces 1and 2 of the work-piece are 154 and 169 respectively which are lesser compared to those of the forged part (191,222 and 284 on the surfaces 3, 5 and 6 respectively). It is also observed that the surfaces which are compressed more show more hardnesses compared to the other surfaces. The inner surface hardness could not be tested because of the limitation of the digital hardness testing machine used.

Analytical Method To Obtain Work-Piece Specifications:

The mathematical formulation to obtain the specifications was based on the assumption that the volume of the work-piece is equal to the volume of cavity to fill (Vazquez, 2000). Hence volume of the work piece geometry and that of the final forging are equated as follows:

$$V_{wp} = V_f \tag{7}$$

$$L_1 = \frac{V_i - \sum_{i=1}^{n} V_C}{\pi r_1^2} \tag{8}$$

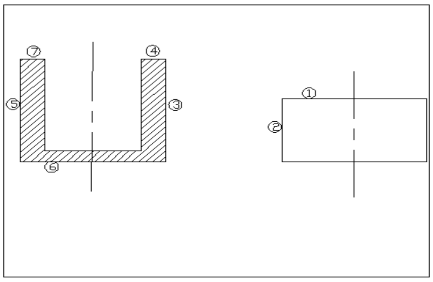
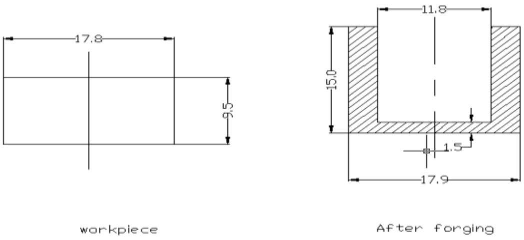


Fig. 1: Forged and unforged part of cup shaped article



workpiece
After forging

Fig. 2: work-piece before forging and after forging

Table 1: Vecker's hardness value for work piece and forged article

Surface number	Vicker's hardness	
	Work piece	Forged part
1	154	-
2	169	-
3	-	191
4,7	-	151,164
5	-	222
6	-	284

The optimum length and radius of the cylindrical work piece for forging of cup shaped article can be obtained from Equation (8). The right hand side of the equation can be reduced by using high modeling packages such as PRO-E and SOLID WORKS. In this work SOLID WORKS 2007 SP4.0 is used for this purpose and the cup shaped article is modeled as per the required specifications and computed its volume. Substituting the volume of the cup shaped article in equation (8) we get:

$$r_1 = \sqrt{\frac{2352}{\pi L_1}} \tag{9}$$

The radius and height of the work-piece can be determined from Equation (9).The value of radius can be computed by assuming the value of height which is calculated for forging as shown in figure (2).

Assuming h_1=9.22mm, the diameter of work-piece is 17.8mm.The aspect ratio (h_1/r_1) is taken as 1.93 to save the energy required for forging process. The same specification work-piece is modeled in SOLID WORKS 2007 SP4.0 and saved in STL format for the FEM analysis and the forging processsimulation is carried out in DEFROM-F3 stress analysis of die as well. Same dimension work-piece of steel (AISI 1045) and aluminum (AISI 1100)work-piece forged in 80 ton capacity machine to compare with the analytical and FEM result.

Steps in optimization of work-piece:

It starts with developing the mathematical equation for the work-piece to achieve the flash-less forging and then developing the CAD model of the optimized work-piece. This model is then transferred to the FEM environment, and analyzed for flash. If no flash is observed then under filling is checked for the process. If no under - filling is found then the process stops, otherwise the process is repeated till no under-filling is achieved.

FE modeling:

The model of punch, die and work-pieces created in SOLIDWORKS2007 SP4.0 licensed version as per the design. For the simulation of forging process the DEFORMF3 is used. The hexahedron elements are used for meshing; the number elements are used for work-piece is 20000, for punch 20732 and for die 20732.The complete assembly is shown in figure 3.

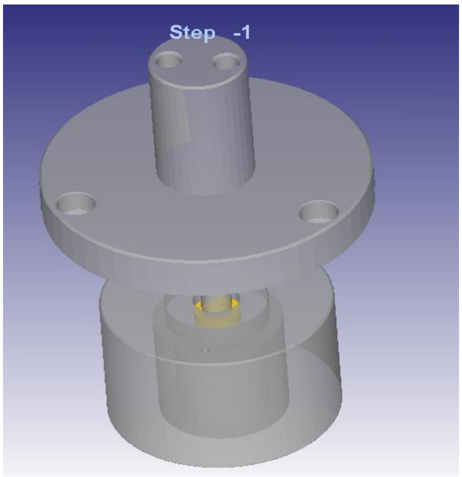


Fig. 3: The assembly of Die, punch and work-piece

Material properties and boundary conditions:

The material properties chosen for the current study are shown in Table 2.The forging process is simulated to study the metal flow and the die stress. The velocity of the punch is 250mm/sec, friction coefficient is 0.15, initial temperature of work-piece, punch and die is 25^0C, punch stroke is 32mm, number of steps are 100 and the step increment is 10. For the die, stress to size ratio is 3, interpolation force tolerance is 0.0001, bottom surface of the die is constrained in X, Y and Z directions, starting step number is 1, number of simulation step is 1, step increment 1, and maximum elapsed process time is 1sec.

Table 2: Material properties of work-piece Die and Punch

Parameter	Work-piece	Die	Punch
Material type	AISI 1045	Tool steel AISI D2	Tool steel AISI D2
Young’s modulus	210GPa	210GPa	210GPa
Poission ratio	0.33	0.33	0.33
Yield strength	1250 MPa (in compression)	3100MPa (in compression)	3100MPa
Hardness	HRC-24	HRC-62	HRC-62

RESULTS AND DISCUSSION

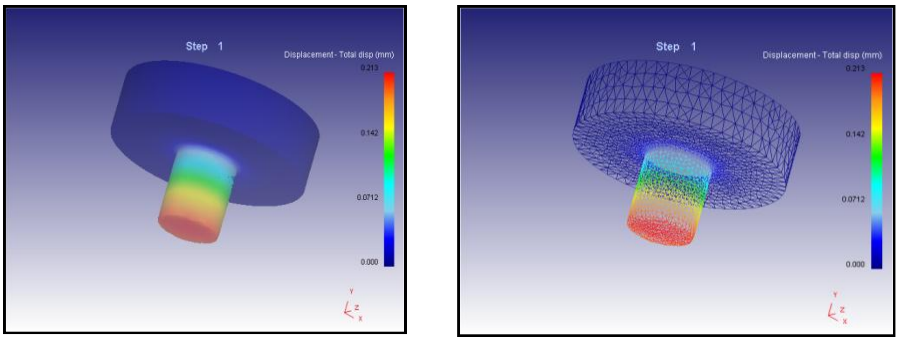
Using equation (8) the various radii are found out and flash is checked. In this equation the diameter is fixed at 18mm and the height is varied.

Deformation in the punch:

In cold forging it is very important to study the elastic deformation in punch. The deformation is calculated to be 0.164mm using the formula:

$$\delta = \frac{PL}{AE} \tag{10}$$

The elastic deformation obtained from FEM analysis is 0.213mm as is clear from figures 4 (a) and (b), and is very close to the analytical results. It can be seen from the figures that the maximum deformation is at the free end of the punch.



4(a) 4(b)

Fig. 4: The simulation result of elastic deformation in the punch (a) Solid model (b) meshed model

In the die the deformation is maximum at the top surface of cavity, i.e. 0.060 mm as shown in figure 5 which is lesser than the punch deformation. These trends are acceptable in the theoretical perspective as well.

Under-filling and volumetric analysis:

An attempt is made to remove the under-filling by filling the corners of the cavity so as to enhance the dimensional accuracy of the final product. A number of iterations are performed using FEM commercial software DEFORM-F3 V6.0. In each iteration, the aspect ratios are varied to find out the optimum value as shown in table 3. The work piece specification is calculated using equation (8) and shape of the work-piece is chosen as cylindrical geometry. Figures 6,7, 8 and 9 depict the under-filling in forging process using different specifications and aspect ratios (Ar = 1.78, 1.81 and 1.87 respectively). It is evident that under-filling occurs at the lower corners of the article, whereas the percentage of under filling is reduce to zero for Ar = 1.93 as shown figure 9.

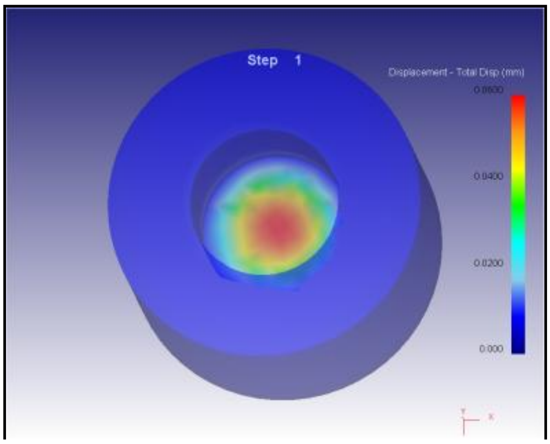


Fig. 5: Elastic deformation in the die.

Table 3: Work-piece volume, flash volume and percentage flash of Preform 2 for various aspect ratios

Cases	Aspect ratio (d/h)			Work-piece volume (mm^3)	Flash volume (mm^3)	% flash
I	1.93			2488.48	30.13	7.97
II	1.87			2438.69	73.95	6.09
III	1.81			2364.03	148.61	3.12
IV	1.78			2320.21	198.4	1.29

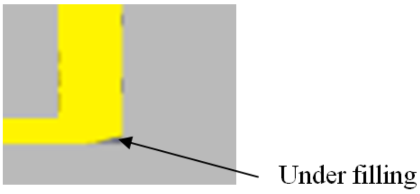


Fig. 6: Sectional view of forging with maximum under-filling (Ar=1.78).

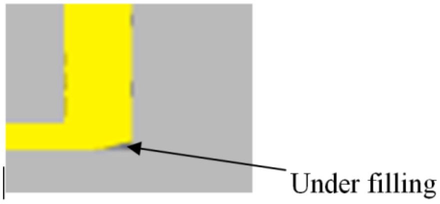


Fig. 7: sectional view of forging with reduced under-filling (Ar= 1.81).

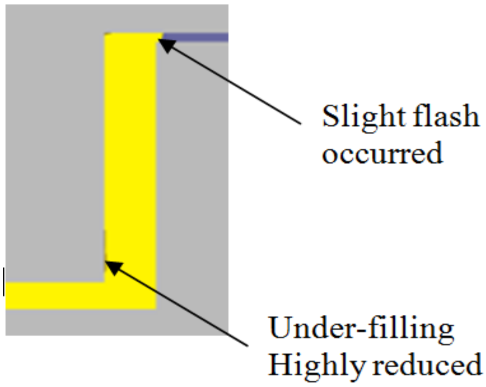


Fig. 8: Sectional view of forging with minimum under-filling with slight flash(Ar = 1.87).

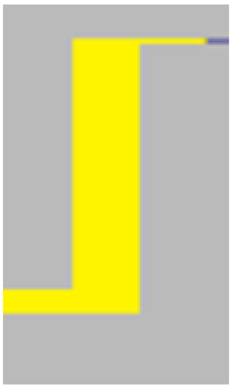


Fig. 9: Sectional view of forging with no under-filling and maximum flash (Ar = 1.93).

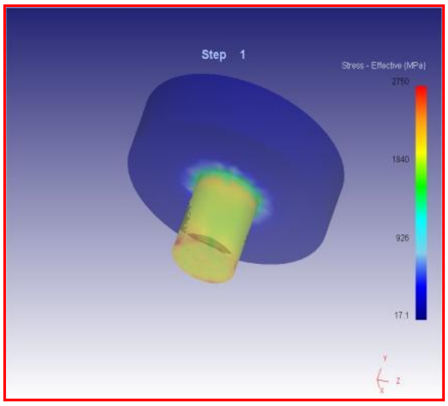


Fig. 10: Effective stress during forging process in punch.

Effect of aspect ratio on forging load:

Table 4 shows the predicted forging load versus aspect ratio (Ar).The maximum forging load (1.33×10^6N) is found to be for the highest Ar (case IV) and goes on reducing at lower aspect ratios. Though the minimum forging load (2.68×10^5N) is observed at the minimum Ar (case I) under filling has occurred at the corners of the cavity. However the under filling is completely eliminated at Ar =1.93, with the maximum forging load.

Table 4: Predicted forging load Vs aspect ratio

Iteration	CASE I	CASE II	CASE III	CASE IV
Aspect ratio (d/h)	1.78	1.81	1.87	1.93
Load prediction (N)	2.68X105	2.76X105	7.64X105	1.33X106

Stress Analysis:

To prevent cracks due to fatigue, it is essential to understand the plastic deformation of die and punch and maximum principal stress. Figure.10 shows the stress distribution in punch, which is maximum at the free end. This maximum stress causes plastic deformation in the punch, which eventually leads to dimensional error in the forged part, in successive forgings. The stress gradually reduces and then increases nearer to the other end. The effective stress is 2750MPa which is quite closer to the yield strength, so the punch dimension has to be optimized to reduce the effective stress. Figure 11 shows the effective stress distribution in the die, the maximum effective stress is 1580MPa. Figure 12 shows that the maximum principal stress in the die is 1200MPa.

Stress distribution in the forged part is also analyzed and presented as in figure13.It is observed that the maximum effective stresses are at the bottom of the article and the minimum at the rear end.

The experimental setup:

To obtain flash-less forging of the cup-shaped product, experiments are conducted at our laboratory, on C-type forging machine of 100 tons capacity as shown in figure 14. The simulated work-piece model IV which produces the minimum flash is selected and fabricated for the experimental work. The mountings and accessories of die and punch assembly are shown in figure 15.The velocity of the punch is set as 250mm/sec. The work-piece and the final product are shown in figure 16.The experimental result is in excellent matching with the simulation result.

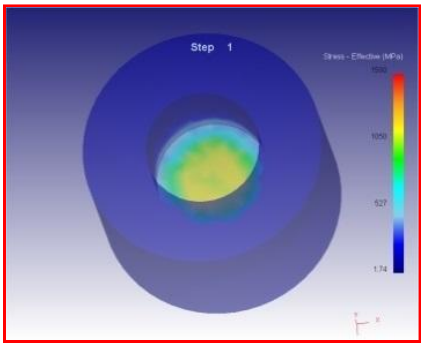


Fig. 11: Effective stress during forging process in the die.

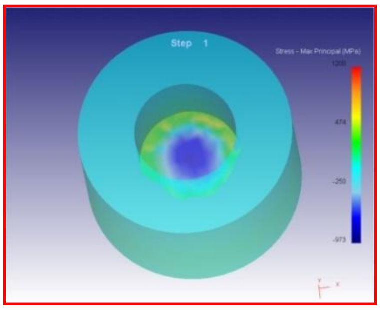


Fig. 12: Maximum principal stress during forging process in the die.

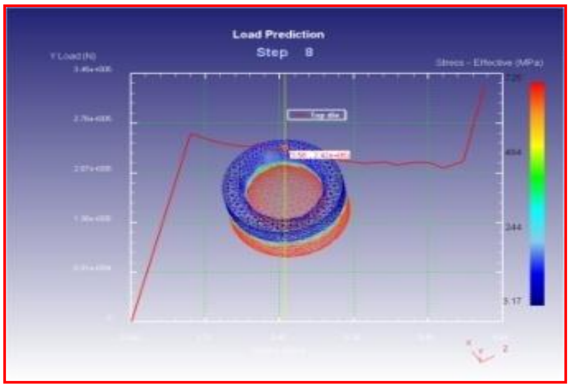


Fig.13: load prediction graph of the forging and effective stress.

Fig. 14: The C-type forging machine used in the study.

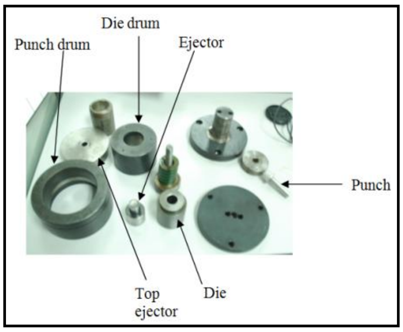


Fig.15: Mountings and accessories of die and punch assembly.

Fig. 16: Work-piece and cup shaped forging produced experimentally.

Conclusions:

Three dimensional finite element simulation and experiment for flash-less cold forging of a cup shaped object has been performed. Stress analysis within the forging die and volumetric analysis of the work-piece were also done. The modeling was done by SOLIDWORKS 2007 SP 4.0 and simulation was performed by DEFORM F-3 V6.0. Mathematical equation was developed to obtain the initial geometry of the work-piece. It has been observed that under-filling decreases with increase in aspect ratio of the work-piece, but the possibility of flash increases. Accordingly the aspect ratio which provides minimum flash with no under-filling has been found to be 1.93. The analytical results and FEM simulated are compared with experimental results and found in good agreement.

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