Backward Simulations using Modified Upper Bound Elemental Technique (MUBET) for Preform Design in Forging Process

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Abstract:

The objective of this research was to develop mathematical models based on modified UBET for forging processes as well as forging preform design of axisymmetric parts. In the modified UBET, the velocity fields are derived based on volume mapping approach and evaluated by minimizing the total energy rate of UBET. The model developed for forging processes is based on MUBET using forward simulations. On the other hand, forging preform design model is based on MUBET using backward simulations. FEM simulations were conducted in order to validate the developed models. The significance of various process parameters such as the intermediate/preform geometry, the optimum aspect ratio of billet, and forming load were determined using the developed method. The results showed that this research was successful in predicting the optimal preform in which maximum material utilization can be achieved. Comparison showed that MUBET can predict the process variables with reasonable accuracy and short run time.

Keywords: Forging pre-form design; Backward simulation; UBET; MUBET; Volume mapping approach;

Introduction

One of the most important computer-aided techniques in simulating and analyzing the metal forming processes is the development of the finite element analysis due to its applications to modern metal forming die and process design. FEM forward simulation has played a significant role in predicting the deformation flow patterns and has improved the quality of the product. However, the main role of FEM is to verify the die designs accomplished by using empirical relationships or based on engineering practice [1]. Usually, a number of pre-forms are needed in order achieve the final complex shape from the initial simple shape with the optimal properties and geometrical tolerance in metal forming processes. Forging pre-form design is computed via backward deformation simulations in which procedure is followed similar to dies design procedure where the die shapes and process parameters are determined based on the final product shape as well as the material properties requirements. Consequently, forging pre-form design process using backward simulation has a very crucial function in forging die design process. Optimizing the entire forging process to obtain the desired forging properties such as achieving proper die-fill, reducing the material waste, reducing the die wear, obtaining the favorable grain flow and the load required can be fulfilled by using adequate and appropriate pre-form [1]. Next section outlines some of the previous research work that have been done in the area of forging pre-form design process.

UBET program has been developed by Lee et al. [2] to analyze the forging load, die filling, and the effective strain for forgings with and without flash gap. The program is applied to both axisymmetric and non-axisymmetric closed die forging as well as plane strain closed die forging with rib-web type cavity. The results obtained from this study were compared with experimental results in which, a good agreement was achieved. UBET was applied to analyze the material flow in a filled die cavity for plane-strain conditions by Hou [3]. The numerical results obtained from UBET were compared with FEM simulations as well as experimental data. The comparison showed a satisfactory agreement. UBET has been proposed by Ranatunga et al. [4], for the design of the flash gap in closed-die forging with rib-web type of cavity for axisymmetric parts. The forging load, the die-cavity filling, effective strain, and strain rate distributions were analyzed using the developed approach. FEM forging simulations were conducted using different die geometries and the results obtained were in good agreement with those predicted by UBET. A new approach is introduced by Yiguo, L., et al. [5], for pre-form design called Simulation Block Technique (SBT) in which, the two half-parts of the forging die is imaginarily separated from their closed position, they move backward from each other in opposite direction of the forward (normal) forging process, so that the initial billet or a pre-form can be obtained, the model incorporates the use of UBET. A pre-form design approach that incorporates both FEM-based forward simulations and UBET-based backward simulations was developed by Liu, Q., et al. [6]. Initially, the material flow information is obtained by FEM forward simulation of test pre-forms, the pre-form is then designed by UBET based on the information obtained previously, finally, the pre-form is tested by FEM forward simulation to check whether or not it satisfy the final design conditions. An axis-symmetric gear-blank forging is used to demonstrate the forging pre-form design, the method was compared with experimental data and showed to be in good agreement. Bramley A., N., [7], has employed TEUBA, which is a UBET-based computer program for the process of forging pre-form design using reverse simulations. This approach is based on reversing the flow by starting from the desired final shape with the die velocities reversed in such a way that the material at the end of the deepest die cavity is considered to have a free boundary and material flows backward up to certain time step where the dies are separated from the billet, which gives the pre-form of the process. A finite element-based inverse die contact tracking method to design the perform die shapes of a generic turbine-disk forging process was used by Zhao, G., et al. [8]. Forward simulations were performed while changing the height-to-diameter ratio until the optimal aspect ratio of the initial billet was obtained. The simulations results show that a net-shape-part can be obtained using the sequence and the new designed pre-form die shapes as well as obtaining parts with free folding defects and reducing the die wear. An optimization approach for the design of intermediate forging die shapes using backward deformation simulation and design optimization was developed by Han, C., S., et al. [9]. This approach could determine the pre-form die shapes from the final part shape by imposing constrains on the plastic deformation of the material. The inverse die contact tracking method was presented by Zhao, G., et al. [10]. Both forward and backward finite element simulations to design the perform shapes in plane strain forging were employed. The sequence of this approach starts with forward simulation of a candidate pre-form into the final product shape. Kang, B., S., et al. [11] presented pre-form shapes design in forging of rib-web shaped plane-strain parts were designed using rigid-plastic finite element method in order to obtain flash-less parts. The pre-form was obtained by changing the aspect ratio- the height to width ratios of the rib geometry used in the analysis. The pre-form obtained in plane strain forging was compared with those of axis-symmetric forging rib-web parts.

Upper Bound Elemental Technique (UBET)

The upper bound theorem was formulated by Prager and Hodge [12] and later modified by Drucker et al. [13,14] by including the velocity discontinuities Kudo [15] introduced the concept of dividing the workpiece into several rigid blocks, obtaining lower upper bounds by changing the shape and number of these blocks. Kobayashi [16] suggested curved discontinuity surfaces for the deformation blocks which gave a better upper bounds for some axisymmetric problems. The upper bound theorem states that the actual energy rate is less than or equal to:

$$W_t = W_p + W_s + W_f \tag{1}$$

$$W_p = \int_V \bar{\sigma}.\dot{\bar{\varepsilon}}.dv \tag{2}$$

$$W_s = \int_s k.|\Delta V|.ds \tag{3}$$

$$W_f = \int_s mk.|\Delta V|.ds \tag{4}$$

Upper Bound Elemental Technique is an energy rate minimization method based on the Upper Bound Theorem for the numerical analysis of metal forming processes. The Upper Bound Theorem is a modeling technique that takes into consideration the total energy rate of the system and produces the velocity distribution by minimizing the total energy rate with respect to the unknown boundary velocities, in which the work-piece is divided into several rigid blocks (elements or features) [17].

Upper bound approach consists of the construction of a kinematical admissible velocity field for a certain deformation process, and a simultaneous minimization of total energy rate gives the upper bound solution for that process. UBET takes into account the elemental strain-hardening effects in an incremental manner and can be applied to rigid-plastic materials to simulate the 3-D plastic flow characteristics in metal forming processes. The UBET is suitable for the analysis and applications of simple and complex metal forming processes [17,18]. In UBET analysis, a kinematical admissible velocity field has to be obtained for each elemental zone. A velocity field at each time step is evaluated by minimizing the total rate of energy consumption. Also, the plastically deforming zone is subdivided into simple rectangular, triangular, brick, and/or prismatic elements linked together with shear surfaces [17].

The major statement of the upper-bound method is, among all kinematical admissible velocity fields, the real velocity field that delivers the minimum value for the internal power, integrated about the entire forming zone. By applying this principle for the ring rolling process, the forming zone in the roll gap will be assembled into elements with the same conditions for the velocity fields. These fields depend on the actual contact situation between ring and rolls. The kinematical admissible velocity fields can be determined by using volume constancy and different boundary conditions. Then the free parameters of one admissible velocity field will be varied in order to minimize the internal power in the deformation zone. The result is a velocity field which is close to the real one and which can be used to calculate the ring geometry at approximately every point in the roll gap [17].

The general procedure when formulating a solution to such a profile rolling is to divide the deformation zone into one or more assumed zones, as shown in (Figures 6.6 and 6.7), throughout each of which the velocity is continuous. In adjacent zones, a different velocity distribution may exist whilst across the interfaces and also on the tool/billet interfaces, a tangential velocity discontinuity may occur. The best velocity distribution is the one that minimizes the value of total power dissipation, which consists of deformation, shear, and frictional power dissipation associated with each element [18]. Thus equation can be rewritten as:

$$W_{total} = \sum W_p + \sum W_s + \sum W_f \tag{5}$$

Modified UBET & Volume Mapping Approach

Based on the volume constancy (volume will remain constant or unchanged), the volume mapping approach can be used to derive the velocity fields, these velocities can be evaluated by minimizing the total power of the upper bound elemental technique (UBET) and therefore this approach is called the modified upper bound elemental technique (MUBET). This approach is used to establish a forging pre-form design strategy in which backward deformation simulation for 2D axisymmetric ring blank gear forging is implemented. For two dimensional (axisymmetric) forging as shown in Figure 1, the velocity fields for a rectangular as well as a triangular element can be derived as given in equation (6), and equation (7) respectively.

$$(w_{i,j} + w_{i,j+1})(r_{i+1,j}^2 - r_{i,j}^2) = 2(u_{i,j}r_{i,j} + u_{i+1,j}r_{i+1,j})(z_{i,j+1} - z_{i,j}) \tag{6}$$

$$u_{i,j}\,2r_{i,j}(z_{i,j+1} - z_{i,j}) + w_{i,j}(r_{i+1,j}^2 - r_{i,j}^2) = w_{i,j+1}(r_{i+1,j}^2 - r_{i,j}^2) \tag{7}$$

The general velocity fields as well as the strain rate fields are based on the incompressibility condition (volume constancy) that is $\dot{\varepsilon}_r + \dot{\varepsilon}_\theta + \dot{\varepsilon}_z = 0$, and are given in Table 1 for both rectangular and triangular elements.

Table 1. General Velocity and Strain Rate fields for Rectangular and Triangular Elements

Rectangular Element	Triangular Element
$u = -\frac{(w_{i,j+1} - w_{i,j})}{2(z_{j+1} - z_j)} r + C\frac{1}{r}$	$u = \frac{r_i u_{i,j}}{r_{i+1} + r_i}(1 + \frac{r_{i+1}}{r})$
$C = \left[u_{i,j} r_i + \frac{(w_{i,j+1} - w_{i,j})}{2(z_{j+1} - z_j)} r_i^2 \right]$	$w = w_{i,j} + \frac{r_i u_{i,j}}{r_{i+1} + r_i}(z_j - z)\frac{1}{r}$
$w = \frac{(w_{i,j+1} - w_{i,j})}{(z_{j+1} - z_j)} z + \frac{(w_{i,j} z_{j+1} - w_{i,j+1} z_j)}{(z_{j+1} - z_j)}$	$\dot{\varepsilon}_r = -\frac{r_i r_{i+1}}{r_{i+1} + r_i} u_{i,j} \frac{1}{r^2}$
$\dot{\varepsilon}_r = -\frac{(w_{i,j+1} - w_{i,j})}{2(z_{j+1} - z_j)} - C\frac{1}{r^2}$	$\dot{\varepsilon}_\theta = \frac{r_i}{r_{i+1} + r_i} u_{i,j} \left(\frac{1}{r} + \frac{r_{i+1} 1}{r^2} \right)$
$\dot{\varepsilon}_\theta = -\frac{(w_{i,j+1} - w_{i,j})}{2(z_{j+1} - z_j)} + C\frac{1}{r^2}$	$\dot{\varepsilon}_z = -\frac{r_i}{r_{i+1} + r_i} u_{i,j} \frac{1}{r}$
$\dot{\varepsilon}_z = \frac{(w_{i,j+1} - w_{i,j})}{(z_{j+1} - z_j)}$	$\dot{\gamma}_{rz} = -\frac{r_i u_{i,j}}{r_{i+1} + r_i}(z_j - z)\frac{1}{2r^2}$
$\dot{\gamma}_{r\theta} = \dot{\gamma}_{rz} = \dot{\gamma}_{z\theta} = 0$	$\dot{\gamma}_{r\theta} = \dot{\gamma}_{z\theta} = 0$

The above velocity and strain rate fields are expressed in terms of the boundary velocities which can be obtained by equations (6 and 7)

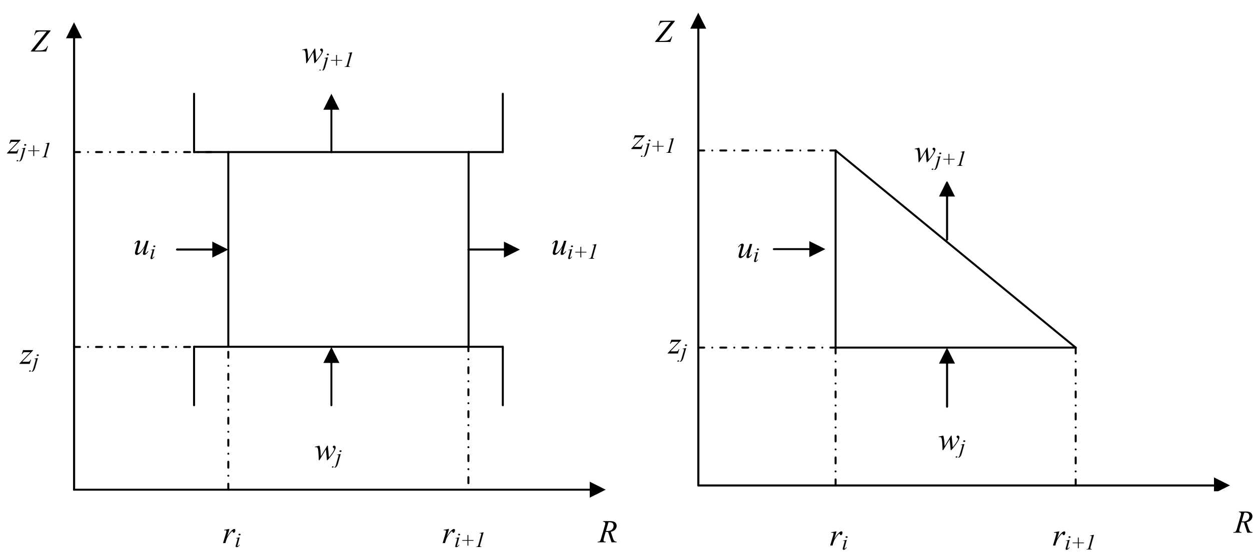

Figure 1. Boundary velocities for rectangular and triangular elements

Forging Backward Simulation Using Modified UBET

Computer-aided simulation, such as FEM, has had a huge impact in modern metal forming die and process design. FEM forward simulation has played a significant role in predicting the deformation flow patterns and has improved the quality of the product. However, the main role of FEM is to verify the die designs accomplished by using empirical relationships or based on engineering practice. Pre-form design is computed via backward deformation simulations in which a procedure is followed similar to die design procedures where the die shapes and process parameters are determined based on the final product shape as well as the material properties requirements. Consequently, pre-form design using backward simulation has a direct and very effective role in forging die design and forging preform design.

The backward deformation simulation process is based on volume mapping approach. Simulation of the inverse deformation process in step-wise way is very much like the forward simulation, where the deformed geometry of the work-piece shape is updated using the boundary velocity fields for the current step. In reverse simulations, the boundary velocity field obtained is reversed to calculate the previous incremental geometry of the billet corresponding to the tools moving back through one increment. The procedure is repeated until the desired separation of the dies is reached or until the dies have moved apart to the extent that one of the dies is no longer in contact with the workpiece. The boundary velocities are found by solving the non-linear system of equations after applying the proper boundary conditions. Typically, these equations can be solved using a suitable numerical optimization technique such as Newton Raphson method.

Figure 2 shows a typical cross section of a final forged with the upper die cavity is filled, the process starts by reversing the movement of the upper die as well as the boundary velocities so that both the billet material as well as the upper die move in a direction opposite to that of forward simulations. In this analysis, the profile of the dies and the work-piece cross-section are approximated by straight line segments as shown in (Figure 2). Based on these line segments, the cross-section of the final part will be divided into triangular or rectangular elements.

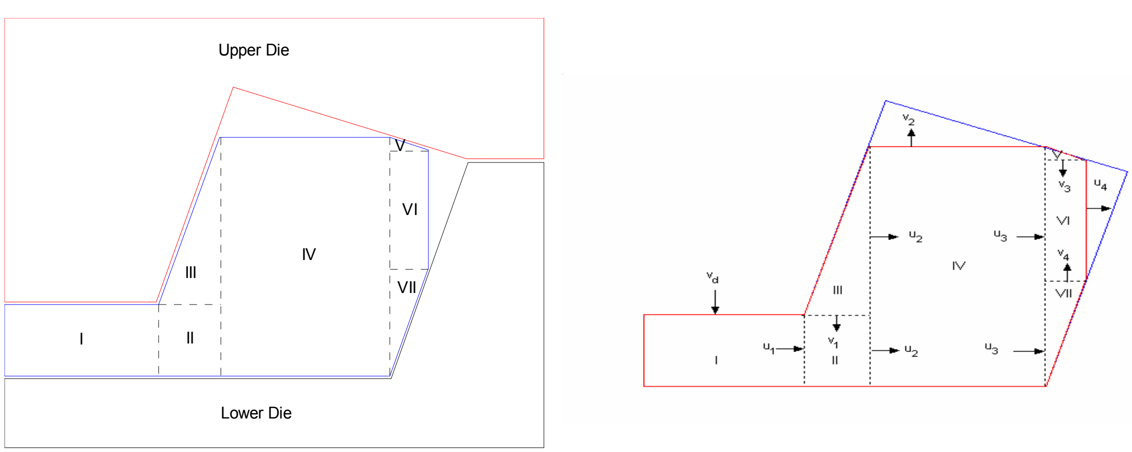

Figure 2. Final process layout including the division of the elements

Backward simulations using volume mapping approach can be carried out by reversing the boundary velocity field obtained to calculate the new backward geometry of the billet corresponding to the upper die moving backward (upward) through one backward increment. The procedure is graphically shown in the following flow chart (Figure 3) and the main steps of this process can be summarized as follows:

- The final product geometry, finisher die and processing conditions are employed to establish the initial UBET model for the reverse deformation simulation.
- Start with final shape (die filled or almost filled)
- The final shape is divided using straight lines segments into a number of elements rectangular or triangular according to the change of slope of the die-surface geometry.
- Kinematical admissible velocity fields are derived based on step 2, by using volume mapping approach.
- Backward simulation is conducted by reversing the boundary velocity fields.
- A backward step is taken to update the work-piece geometry and die position based on the velocity field from the previous backward step.
- The procedure is repeated until the desired separation of the dies is reached.
- When the stopping criterion is satisfied, the backward simulation is terminated.
- FEM forward simulations is then carried out in order verify the pre-form obtained by backward simulations.

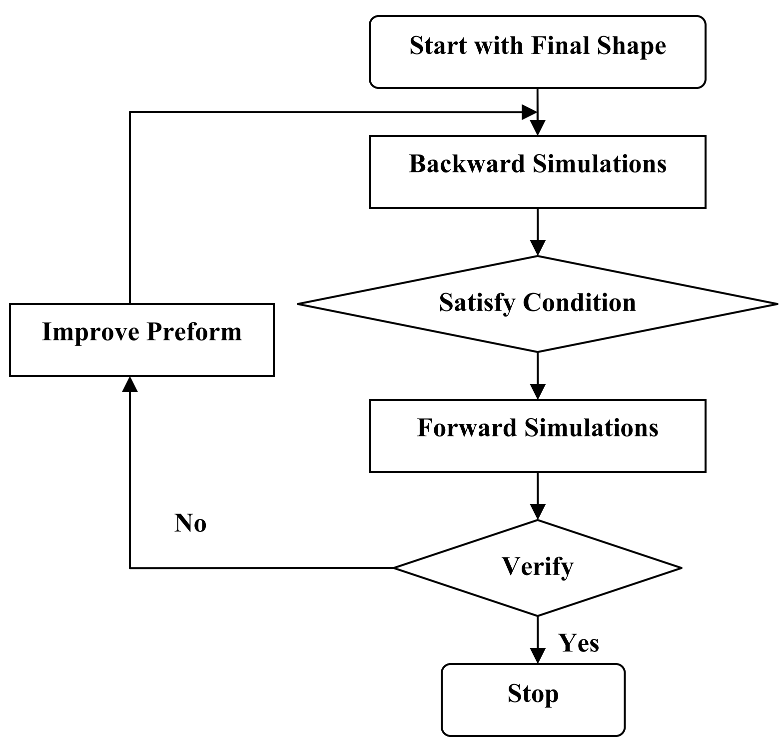

Figure 3. Flow chart of the forging preform design process

Results & Discussion

The forging of a ring gear blank for differentials in automobiles is considered. A volume mapping technique was used to determine the optimum intermediate shape for forging using backward simulation. The final part is divided into features, which provide an approximated profile consisting of a number of rectangular and triangular elements. It was intended from the present work to achieve proper forging strategy of the ring gear blank forging process through optimizing and reducing the following:

(a) Material wastage during the multi-stage forging of ring gear blanks
(b) Reduce the number of forging (and material handling) stages from 3 to 2, and
(c) The initial billet temperature from about 2100^{o} F to about 1800^{o} F

The above tasks were accomplished by conducting a backward simulation using a volume mapping technique and iterative forward simulation using Finite Element Analysis of the gear blank forging process. Usually, a number of preforms are needed in order to achieve the final complex shape from the initial simple shape with the optimal properties and geometrical tolerance in metal forming processes [2]. The ring gear blank forging process is a multi-stage forging process in which three stages are currently involved in manufacturing the final part. These three current stages were simulated using SuperForge in order to verify the commercial software. Both 2D (axisymmetric) and 3D forging simulations were conducted for this purpose. In order to reduce the number of forging (and material handling) stages, a preform has to be obtained so that the final shape can be attained by only two stages, which will reduce the cost and time of material handling as well as the material wastage. Based on volume mapping approach, the kinematical admissible velocity fields are derived, and the preform geometry of the second stage forging was obtained by backward simulations. The martial used was steel AISI-4337 and was performed at temperature of 2100^{o} F and then reduced to about 1800^{o}F. Using the pre-form obtained by volume mapping approach (Figure 4), the preform is verified by conducting forward computer simulations. The final shape of the ring gear was achieved using the preform.

Several forward computer simulations including 2D (axis-symmetric) and 3D forging simulations were conducted in order to optimize the ring gear forging process. The forming temperature was reduced from about 2100^{o} F to about 1800^{o} F which will have a huge impact in increasing the die life time. Also, the martial wastage can be reduced from about 5 % to about 17.5 % volume reduction. A volume reduction of 5 % to about 10 % with 0.1 in and 0.2 in machining allowance could be achieved. The forming process can be carried out using flash-less precision forging since the die load of the 2nd stage is within the press capacity.

Up to 17.5 % volume reduction can be achieved by conducting net shape forging in which only 0.02 in machining allowance is used. The 1st stage forging was performed using different aspect ratios (height to diameter) of the initial stock (billet). The simulations results for the net shape forging (case 5) as well as the die load for the two stages are shown in Figure 5 and Figure 6 respectively, also the process parameters of this case are summarized in Table 2. It was found from the simulations that the effective plastic strain can be minimized using shorter billets. The simulations conducted for the net shape forging as well as the process parameters are given in Table 2.

The forging of a ring gear blank for differentials in automobiles is considered. A volume mapping technique was used to determine the optimum intermediate shape for forging using backward simulation. The final part is divided into features, which provide an approximated profile consisting of a number of rectangular and triangular elements. The development of a volume mapping technique to arrive at an optimum pre-form/blocker forge geometry to minimize material usage and also reduce the number of forging stages was considered. A 2-D (axis-symmetric) and 3D computer model were used to simulate the forging process (forward simulation) and to ensure proper die fill. The simulations showed that the present method can successfully determine the optimum intermediate (preform) shape of the forging process. The significance of various process parameters, such as the intermediate geometry, the optimum aspect ratio of billet, forming temperature, and forming load were determined using the simulations results.

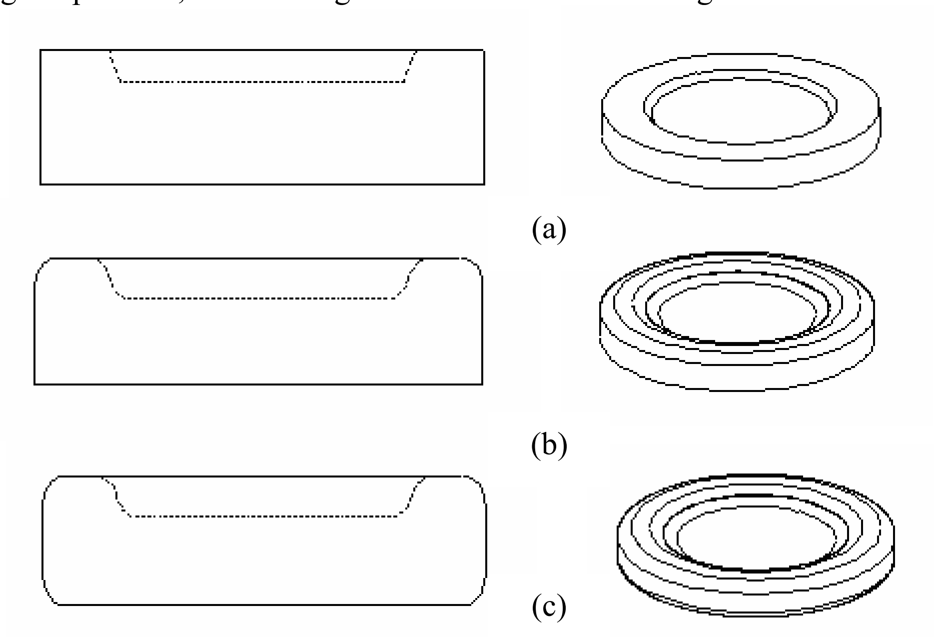

Figure 4. (a) Pre-form obtained by volume mapping approach
(b) Modified pre-form (rounded corners from the top)
(c) Modified pre-form (rounded corners from the top & bottom)

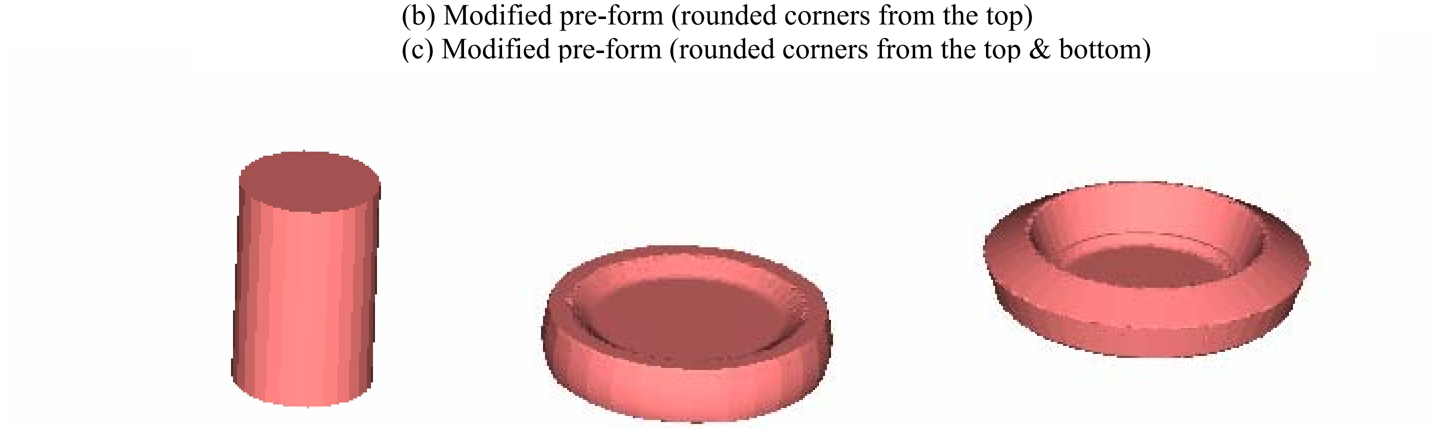

Figure 5. Initial, intermediate, and final shapes of the forging process

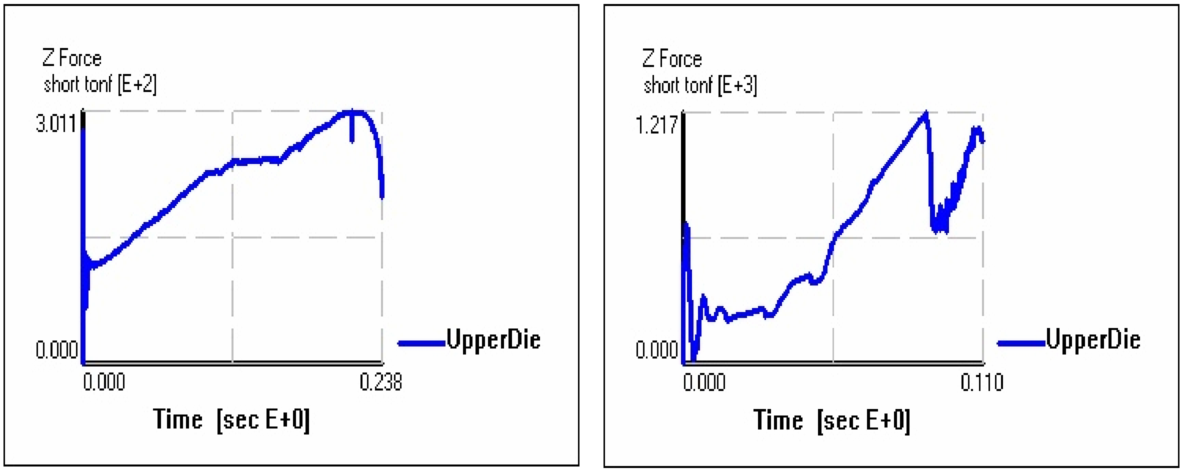

Figure 6. Die load vs Time for stage 1 and stage 2

Table 2. Process input parameters

Case	Vol Red (%)	Height (in)	Dia (in)	Stroke (in)	Temp (^oF)	Die Temp (^oF)	Max Force Ktonf	Flash Thick (in)	Time (sec)	Die Fill
1	0	6.5	3.5	0.98	1800	400	3.514	0.17	0.108	1
2	5	6.175	3.5	1.01	1800	400	1.679	0.14	0.111	1
3*	5	6.175	3.5	1.01	1800	400	1.920	0.14	0.111	1
4	10	5.85	3.5	1.06	1800	400	1.3	0.09	0.113	1
5**	17.5	5.36	3.5	1.0	1800	400	1.217	0.1772	0.1024	1
6***	17.5	5.36	3.5	1.0	1800	400	1.6	0.1772	0.1024	1

* Precision flash-less forging ** Net shape forging ***Centered lower die (stage 1)

Conclusion:

In this research, the development of a volume mapping technique to arrive at an optimum pre-form/blocker forge geometry to minimize material usage and also reduce the number of forging stages of the ring gear blank forging (real problem from industry) was considered. A 2D (axis-symmetric) and 3D computer models were used to simulate the forging process (forward simulation) and to ensure proper die fill. The simulations showed that the present method can successfully determine the optimum intermediate (preform) shape of the forging process. From the simulations results, it can be concluded that the developed method has the capability to determine the significance of various process parameters, such as the intermediate geometry, the optimum aspect ratio of billet, forming temperature, and forming load. Also, from optimizing the different process parameters through the simulations, all of the below tasks were met:

- Forging stages were reduced from 3 stages to 2 stages.
- The final shape of the ring gear blank was achieved with complete die fill using the pre-forms obtained by volume mapping approach.
- The initial billet temperature can be reduced to 1800^o F.

- Material wastage can also be reduced to about 10%.
- The forging process can be carried out using flash-less precision forging since the load obtained was within the press capacity.
- The grain flow pattern seems to be acceptable.
- Different aspect ratios were used in the simulations in order to minimize the effective plastic strain.
- The effective plastic strain of the material was minimized using shorter billets.
- The final stage can be carried out using net shape forging in which material wastage can be reduced to about 17.5 %.

Based on the above, it can be concluded that the developed method has the capability to reduce the number of forging stages. Thus will reduce the material handling, the material wastage as well as reduce the cost of the operation, with the large volume produced of the part in industry.

References

[1] Altan, T., Oh, S., Gegel, H., Metal Forming Fundamentals and Applications, American Society for Metals, 1995.

[2] Lee, J., H., Kim, Y., H., and Bae, W., B., "A Study on Flash and Flashless Precision Forging by the Upper Bound Elemental Technique" *Journal of Material Processing Technology* 72 (1997) 371-379.

[3] Hou, J., "A Plane-Strain UBET Analysis of Material Flow in a Filled Deep Die Cavity in Closed Die Forging" *Journal of Material Processing Technology* 70 (1997) 103-110.

[4] Ranatunga, V., Gunasekera, J., Frazier, W., and Hur, K., "Use of UBET for Design of Flash Gap in Closed-Die Forging" *Journal of Material Processing Technology* 111 (2001) 107-112.

[5] Yiguo, L., Sheng, S., "Reverse Simulation using the Simulation Block Technique and its Application in the Precision Forging Process" *Journal of Material Processing Technology* 63 (1997) 244-247

[6] Liu, Q., Shichun, W., Sheng, S., "Preform Design in Axisymmetric Forging by a New FEM-UBET Method" *Journal of Material Processing Technology* 74 (1998) 218-222

[7] Bramley A., N., "UBET and TEUBA: Fast Methods for Forging Simulation and Preform Design" *Journal of Material Processing Technology* 116 (2001) 62-66

[8] Zhao, G., Zaho, Z., Wang, T., and Grandhi, R., V., "Preform Design of a Generic Turbine Disk Forging Process" *Journal of Material Processing Technology* 84 (1998) 193-201

[9] Han, C., S., Grandhi, R., V., and Srinivasan, R., "Optimum Design of Forging Die Shape using Nonlinear Finite Element Analysis" *AIAA Journal* vol. 31, No. 4, April 1993

[10] Zaho, G., Wright E., and Grandhi, R., V., "Computer Aided Preform Design in Forging using the Inverse Die Contact Tracking Method " *International Journal of Machine Tools and Manufacturing* 36 (1996) 755-769

[11] Kang, B., S., Lee, J., H., Kim, B., M., Choi, J., C., "Process Design in Flashless Forging of Rib-Web Shaped Plane Strain Components by the Finite Element Method" *Journal of Material Processing Technology* 47 (1995) 291-309

[12] W. Prager, P.G. Hodge, Theory of Perfectly Plastic Solids, Wiley, New York, 1951.

[13] D.C. Drucker, H.J. Greenberge, W. Prager, J. Appl. Mech. –Trans. ASME 73 (1951) 371.

[14] D.C. Drucker, W. Prager, H.J. Greenberge, Quart. Appl. Math. 9 (1952) 381.

[15] H. Kudo, Int. J. Mech. Sci. 1 (1960) 229.

[16] S. Kobayashi, E.G. Thomsen, Int. J. Mech. Sci. 7 (1958) 437.

[17] Jia, Z., "An Integrated Analysis and Design Method for Metal Forming Processes", Ph.D. Dissertation, Ohio University, 1998.

[18] Ranatunga, V., "Modeling of Profile Ring Rolling with Upper Bound Elemental Technique" Ph.D. Dissertation, Ohio University, 2002.