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UBET-Based Numerical Modeling of Bulk Deformation Processes

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The paper summarizes the development of numerical procedures for modeling bulk deformation process and preform designing techniques based on the upper bound elemental technique (UBET). UBET has a unique place where an approximate, but faster solution is needed for decision making. In designing and optimizing multistage forging and profile ring-rolling processes, an approximate solution can be used to identify the most influential process parameters. Once an optimum combination of process conditions are determined, computationally intensive, but more accurate finite element analysis can be used to verify and refine results. In this paper, UBET procedures for closed-die forging and profile ring rolling are highlighted. Experimental investigations are used to validate the model predictions. Also, the UBET-based preform design tool is presented as a process and die design tool for multistage forging processes. Application of these techniques is presented with evidence of effective material usage and extended overall die-life.

Keywords metal forming, profile ring rolling, UBET, upper bound elements

1. Introduction

The design of dies and preforms has moved to a new paradigm with the introduction of numerical simulation tools such as finite element analysis (FEA) and upper bound elemental technique (UBET) for bulk-deformation processes. In addition to these numerically intensive techniques, other computer-based analytical techniques can be used for quicker but simpler solutions. All of these techniques have the potential to increase process efficiency and reduce material wastage in bulk deformation processes such as forging, rolling, and extrusion. General-purpose nonlinear FEA codes are capable of simulating three-dimensional (3-D) deformation processes. Unlike forging and extrusion processes, profile ring rolling requires the most numerically intensive calculations because of the simultaneous deformations in the radial, axial, and circumferential directions. Methods to control the degree of freedom of the problem can lead to the loss of important information during the simulation. As an example, simulations based on two-dimensional (2-D) FEA models may not be useful for predicting circumferential ring growth, die underfill, etc., in a profile ring-rolling simulation. To develop initial preform shapes and die design, simpler and quicker design methods are needed. These quick-execution tools can be applied at earlier design stages to narrow-down the design space and evaluate variety of process-design options. Detailed analyses with FEA simulations are useful in refining, verifying, and establishing these initial designs. The paper summarizes the recent application of UBET on the number of forming processes, including closed-die forging, profile ring-rolling, and preform designing for closed-die forging.

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UBET is a valuable modeling technique in solving metal forming problems, because an upper bound solution ensures a conservative effect. The technique involves the construction of a kinematically admissible velocity field for a given deformation process. Simultaneous minimization of total energy rate with respect to the suggested velocity field provides the so-called "upper bound solution" for the process. The upper bound solution was originally formulated by Prager et al. (Ref 1). The technique was further developed by Drucker et al. (Ref 2), followed by Kudo (Ref 3) and Kobayashi et al. (Ref 4) at the early stages. In recent years, Bramley et al. have successfully applied UBET-based simulation tools on many forming processes, including backward simulation of forging for preform design (Ref 5, 6). Ranatunga et al. applied UBET for modeling closed-die forging and profile ring-rolling processes (Ref 7-9). Alfozan et al. (Ref 10) used UBET for devising a backward-simulation tool for modeling profile ring rolling. Almohaileb et al. (Ref 11) extended the approach to design preforms for closed-die forging.

In UBET analysis, a plastically deforming region is subdivided into simple rectangular, triangular, brick, and/or prismatic elements linked together with shear surfaces. According to the upper bound theory, a kinematically admissible velocity field that minimizes the total work done, is the actual velocity field. From such a field, the actual work done can thus be derived, although in practice the actual field may never be completely determined. The theorem states that the actual power is less than or equal to π where:

$$\pi = \int_V \bar{\sigma}\dot{\bar{\varepsilon}}\, dv + \int_A k|\Delta V| dA + m\int_A k|\Delta V| dA \qquad \text{(Eq 1)}$$

where $\bar{\sigma}$ is the effective stress, $\dot{\bar{\varepsilon}}$ is the effective strain rate, k is the shear yield strength of the material, and m is the friction factor between rolls and workpiece; V is the deforming material volume, and A is the area of the shear surface. The general procedure when formulating a solution in UBET is to divide the deformation zone into one or more assumed zones throughout each of which the velocity is continuous. In adjacent zones, a different velocity distribution may exist while across the interface, and also on the tool-workpiece interfaces, a tangential velocity discontinuity may occur. The best velocity distribution is the one that minimizes the value of π in Eq 1.

The function π in Eq 1 represents the summation of volume and surface integrals evaluated over the entire deforming body. If the deforming body is divided into M elements interconnected at N element boundaries, then the value of the functional π may be written as:

$$\pi = \sum_{m=1}^{M} \pi^m(\upsilon) \qquad \text{(Eq 2)}$$

where $\pi^m(\upsilon)$ represents the same integral in Eq 1 but evaluated to the mth element. The velocity field υ_i inside this element is expressed in terms of the associated element boundary velocities. To find the minimum value of the functional π of Eq 2, it is necessary to solve the system of equations given by:

$$\frac{\partial \pi(\upsilon)}{\partial \upsilon_i} = 0, \ (i = 1, \ldots, N) \qquad \text{(Eq 3)}$$

With the assumptions of the continuity and existence of the derivatives, the value of $\partial\pi/\partial\upsilon$ evaluated at an assumed solution point $\upsilon = \upsilon_k(n)$ can be written with the help of Taylor expansion as:

$$\left.\frac{\partial \pi}{\partial \upsilon_i}\right|_{\upsilon_k(n)} = \left.\frac{\partial \pi}{\partial \upsilon_i}\right|_{\upsilon_k(n-1)} + \left.\frac{\partial^2 \pi}{\partial \upsilon_i \cdot \partial \upsilon_j}\right|_{\upsilon_k(n-1)} \Delta\upsilon_j(n) + \ldots \qquad \text{(Eq 4)}$$

If $\Delta\upsilon_j$ are small enough, then $(\Delta\upsilon_j)^2$ and all other higher-order terms can then be neglected. With this, Eq 3 can be modified for Newton-Raphson iterative method as:

$$\left.\frac{\partial^2 \pi}{\partial \upsilon_i \cdot \partial \upsilon_j}\right|_{\upsilon_k(n-1)} \Delta\upsilon_j(n) = \left.\frac{\partial \pi}{\partial \upsilon_i}\right|_{\upsilon_k(n-1)} \qquad \text{(Eq 5)}$$

In this equation, $\upsilon_k(n-1)$ represents the input values obtained from the previous solutions, and $\Delta\upsilon_j(n)$ is the correction value obtained from the present iteration. Eq 5 can also be written in the matrix form by:

$$[K]\{\Delta\upsilon\} = \{f\} \qquad \text{(Eq 6)}$$

where $[K]$ is called the stiffness matrix. Once the solution of Eq 6 for $\Delta\upsilon_j(n)$ is obtained, the assumed velocity $\upsilon_j(n)$ is updated according to:

$$\upsilon_j(n) = \upsilon_j(n-1) + \Delta\upsilon_j(n) \qquad \text{(Eq 7)}$$

The value of the load derived from the suggested approximate velocity field is necessarily higher than the actual load required by the process, because the real velocity field needs a minimum of energy. Therefore, the predicted load represents an upper bound to the actual forging load.

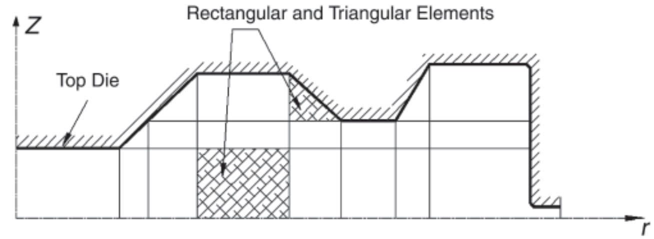

Fig. 1 Discretization of the deformation zone into known UBET elements

2. UBET for Closed-Die Forging

Simulation of closed-die forging is one of the most widely discussed topics among the bulk-deformation processes. Numerous attempts have been made in modeling closed-die forging using upper bound-based techniques (Ref 12-15). The application of UBET in closed-die forging of a fairly complicated disc is shown in Fig. 1. In this figure, the deformation zone is represented by a collection of rectangular and triangular UBET elements. The unknown velocities in the deformation zone are found by minimizing the total energy dissipation expressed by Eq 1. Once the velocities are found, UBET can predict the forging load and the strain rates in each element. As an illustration, consider a flashless closed-die forging of this geometry modeled with UBET.

Forging load, predicted by FEM, UBET, and slab methods, for this simple forging case are given in Table 1 and plotted against the percentage die-fill as in Fig. 2. The value of the forging load derived from the approximate velocity field derived from UBET is necessarily higher than the actual load required by the process, because the real velocity field needs a minimum of energy. Therefore, the predicted load represents an upper bound to the actual forging load.

In the given forging case, the required forging load increases as the material is pressed into the die cavity to fill the corner. Based on the comparison of results between FEM and UBET, it can be concluded that the upper-bound loads are higher than the corresponding FEM loads, but closely follows the trend. Also, the load prediction from the slab method is lower than both FEM and UBET since the slab method gives a lower bound to the load.

3. UBET for Profile Ring Rolling

Shape rolling of seamless rings constitutes an efficient manufacturing process offering excellent material yield, energy conservation, and component production, all of which require a minimum of subsequent machining operations. An increasing number of rings are being produced from high-temperature titanium and nickel-based superalloy materials for gas turbine engine parts such as vane and fan casings, exhaust casings, turbine shrouds, and combustion liners. With the increasing cost of superalloy raw materials and growing demand for cost-competitive parts, the importance of ring rolling to contoured shape becomes an increasingly important factor. Currently, simulation of profile ring rolling requires application of highly time consuming three-dimensional finite element techniques. Any technique that can aid designers on developing ring-rolling process schedules, designing perform shapes, and reducing material utilization will have tremendous impact on the

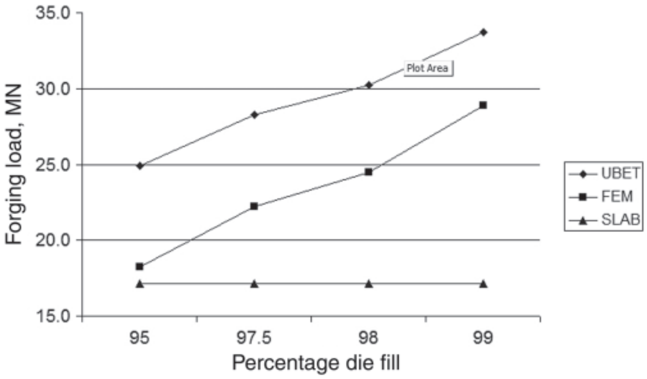

Fig. 2 Comparison for forging loads against percentage die fill

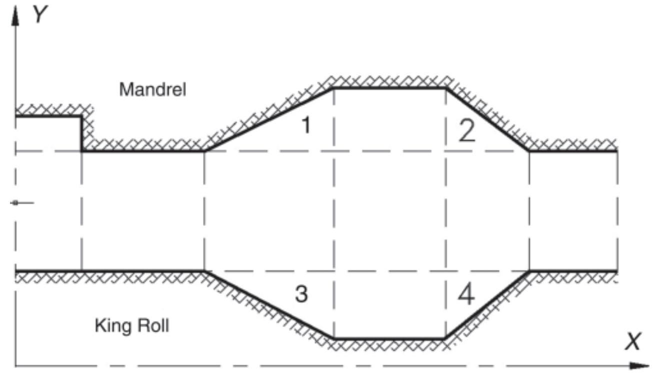

Fig. 3 Orientation of different triangular and rectangular elements on a ring cross-section

Table 1 Summary of loads predicted by UBET, FEM, and slab methods

Die fill, %	UBET load, ×10^6 N	FEM load, ×10^6 N	Slab load, ×10^6 N
95.0	24.9	18.2	17.1
97.5	28.3	22.2	17.1
98.0	30.2	24.5	17.1
99.0	33.7	28.9	17.1

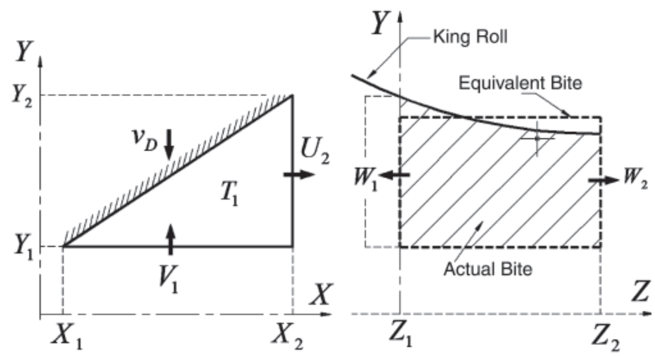

Fig. 4 Boundary velocities for triangular prismatic element

manufacturing cost. UBET is a rapid load estimating technique that has potential to meet these needs and therefore it's application to the unique three-dimensional flow situation experienced in profile ring rolling has been explored widely in the past (Ref 9, 10, 16-19). In the discussion that follows, the authors will highlight number of important steps taken toward implementing UBET procedures for modeling profile ring-rolling process.

3.1 Simplified Element Velocity Fields

An important step in UBET procedure is to propose a velocity field, which will resemble the actual velocity field as closely as possible. But if the element velocity field is complex, it is difficult to satisfy the compatibility of velocity along the boundaries between the elements. Therefore, as a preliminary approach, elements with simple velocity fields have been used to represent the actual velocity field and increase the number of elements to closely represent the actual velocity field. In the following analysis, a cross-section of a selected ring is represented by a combination of triangular prismatic and rectangular brick elements. The three-dimensional nature of deformation is captured by considering the velocities in the bite direction.

3.2 Velocity Fields for Triangular Elements

The triangular elements are basically used to model the inclined faces of the ring profile. Therefore, the triangular element always shares one edge with the boundary (Fig. 3). As an example, consider the boundary velocities and directions for triangle T_1 shown in Fig. 4. According to the figure, the velocity field will be different if it is in contact with mandrel or king rolls. If the element is in contact with the mandrel roll, the contact face velocity V_D is equal to the velocity of the mandrel. In contrast, if it is in contact with the king roll, velocity V_D will be zero because the king roll does not move toward the center of the ring. To simplify the velocity field resulted by the curvature of the die in the Z direction, a linear velocity field is used with a bite being approximated by a rectangle (Fig. 4).

3.3 Velocity Fields for Rectangular Elements

The rectangular element is the most widely used element in current UBET implementation. Unlike the triangular element, this element can be placed both along the roll profiles as well as inside the ring cross-section, with a linear velocity field for all rectangular elements. Consider the boundary velocities given in Fig. 5. If the element is on the boundary of the king roll, the boundary velocity V_1 is zero. Similarly, if the element is on the boundary of the mandrel, the boundary velocity V_2 is equal to the velocity of the mandrel. Velocity in the Z direction is similar to the triangular element. Because the entry and exit sections remain planar during deformation, velocities at entry and exit will be the same for all the elements.

3.4 Discretization of the Ring Cross-Section

In UBET analysis, only the portion of the ring between mandrel and king roll (bite) is selected because the rest of the ring is under rigid-body motion (Fig. 6). UBET implementation imposes a *virtual mesh* on the region between the two rolls and allows material flow through this virtual mesh. The virtual mesh consists of rectangles and right-angled triangles. The region between the mandrel and the king roll is divided into triangular and rectangular elements according to Fig. 7. The actual cross-section of the ring with machining envelope is shown in Fig. 7a, and the generated UBET mesh with rectangular and triangular elements is shown in Fig. 7b.

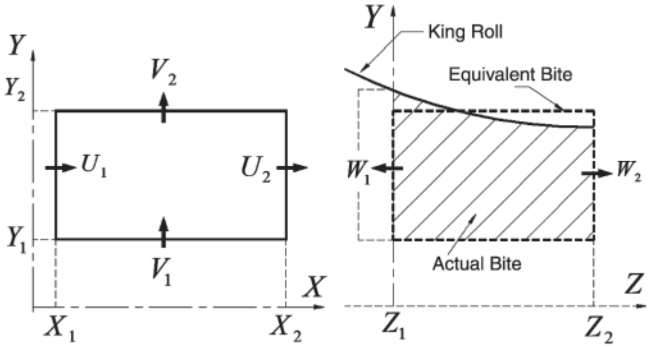

Fig. 5 Boundary velocities of the rectangular brick element

Fig. 6 Section of the ring under deformation between the two rolls

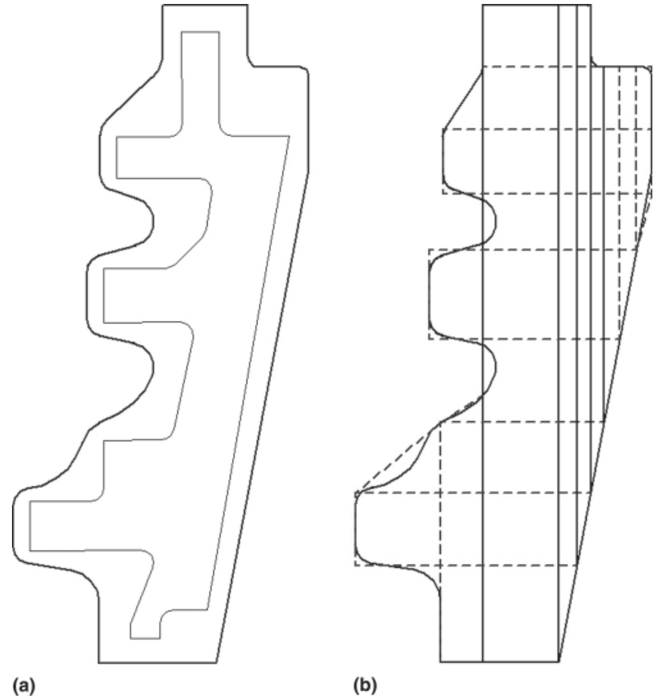

Fig. 7 Cross section of a typical ring; (a) cross section with machining envelope and (b) discretized section with UBET elements

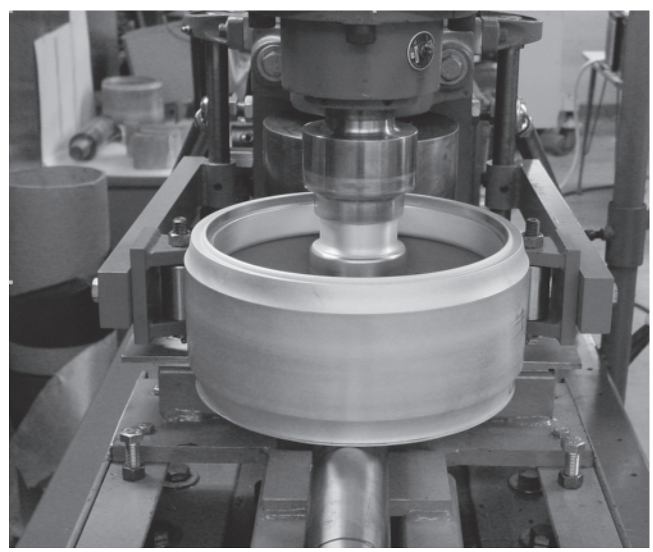

Fig. 8 Experimental profile ring-rolling machine at Ohio University

3.5 Experimental Validation

The UBET program can produce the dimensions of the intermediate ring cross section after every revolution of the ring. To validate the UBET results, it is necessary to experimentally obtain the values of the intermediate ring cross section and other process variables, such as roll separation force, temperature, and strain rate. Alfozan et al. (Ref 10) recently conducted a number of profile ring-rolling experiments and reported the comparisons between experimental results and UBET predictions. These comparisons were conducted on a radial ring-rolling machine that does not have any restriction on axial expansion of the ring (Fig. 8). In addition to these experimental validations, Wagner-Banning Rolltech software was used to generate simulated data for radial-axial-type ring rolling. The Rolltech is a well-established software tool widely used in industry to produce simulation-based data for hot rolling of rings limited to rectangular cross-sections. Rolltech uses slab-based analysis technique for the prediction of roll torque and force predictions. The software tool is developed by SMS Wagner-Banning (http://www.sms-eumuco.de/en/) for control and simulation of their ring-rolling machines.

Simulated data for widely used high-temperature alloys have been used for the validation of UBET results. Comparison of UBET and Rolltech results on the variation of ring diameter with time as given in Fig. 9 for INCO-718 material shows that the two curves follow closely as the deformation progresses. Figure 10 gives the variation of roll separation force with time. Throughout the deformation, UBET has a higher value for roll separation force. The load predicted by UBET deviates from the Rolltech value towards the end of the simulation, but they follow a similar trend.

4. Forging Backward Simulation Using Modified UBET

Finite element-based computer-aided simulation tools have a considerable impact on the success of modern metal forming

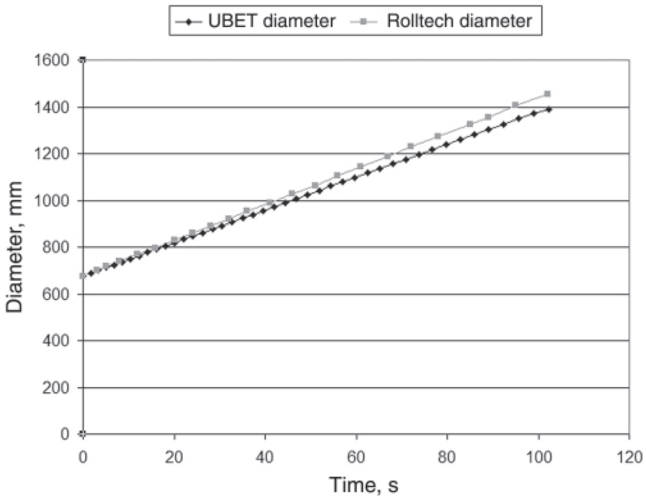

Fig. 9 Variation of ring diameter with time for INCO-718 material

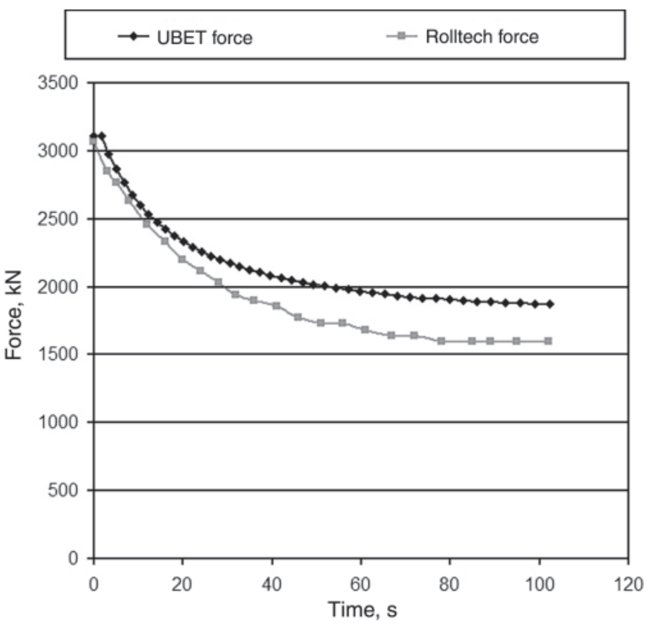

Fig. 10 Variation of roll separation force with time for INCO-718

die and process design techniques. The main role of the finite element based simulations is to verify that the forming process will produce a sound product. But to design a preform that can yield the expected outcomes, other computational procedures are needed. A promising solution that has been used to design the preform geometries is the backward simulation of the deformation process. Numerous computational techniques have been tested for the implementation of backward simulation of deformation process. In this section, the authors highlight the progress made with UBET on implementing backward simulation of deformation processes (Ref 11).

In the modified UBET implementation for backward simulations, the unknown velocity fields are estimated based on the volume mapping approach and evaluated by minimizing the total energy rate of UBET. During the stepwise simulation of the deformation process, the deformed geometry of the workpiece 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 numerically solving the nonlinear system of equations while satisfying the external and internal boundary conditions. Once the boundary velocity field is obtained, a new backward geometry of the billet is found by updating the previous geometry by multiplying the velocity field with the time increment.

In the process of validating this technique, forging of a ring gear blank has been considered. With the help of combined volume mapping and UBET technique, an optimum intermediate shape for forging is produced. The final part is divided into elements based on geometric features, which provide an approximated profile consisting of a number of rectangular and triangular elements. The main objective of the forging simulation is to design the stages of the gear-blank forging process while reducing

- material wastage during the multistage forging of ring gear blanks
- number of forging (and material handling) stages from 3-2
- initial billet temperature from about 1150 °C (2100 °F) to about 980 °C (1800 °F)

Several forward computer simulations including 2D (axisymmetric) and 3D forging simulations were conducted to optimize the ring gear forging process. With the introduction of optimum preform geometry, the forming temperature was reduced from about 1150 °C (2100 °F) to about 980 °C (1800 °F), which will considerably impact the die life. Also, it was possible to reach a 17.5% volume reduction of material wastage by properly designing the forging preform.

5. Conclusions

The most basic approach for design of forming dies and for selecting process variables, such as forming temperature and feed velocity, is based on the use of build and test methods. Use of these methods will result in high tooling and setup costs and longer lead times before production. Many limitations of build and test methods have been overcome through the use of process models based on computer simulation and optimization techniques. UBET has a unique place where an approximate, but quick solution is needed for decision making. In designing multistage forging and profile ring-rolling processes, an approximate solution can be used to identify the most influential process parameters. Once an optimum combination of process parameters is reached, computationally intensive but more accurate techniques such as FEM can be used to verify the forming parameters. Additionally, a fewer number of forming trials can be conducted once the most influential process parameters are identified.

UBET procedures have been developed and tested for validity on profile ring-rolling and closed-die forging processes. Additionally, UBET has demonstrated that the reverse simulations can assist in selecting preform geometries for a forging process. These simulations have revealed some of the important process parameters that can be optimized to achieve sound forged and rolled products. Also, simulations have been used effectively for saving materials and extending die life, which will eventually lead to reduction of the overall cost associated with forming operations.

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