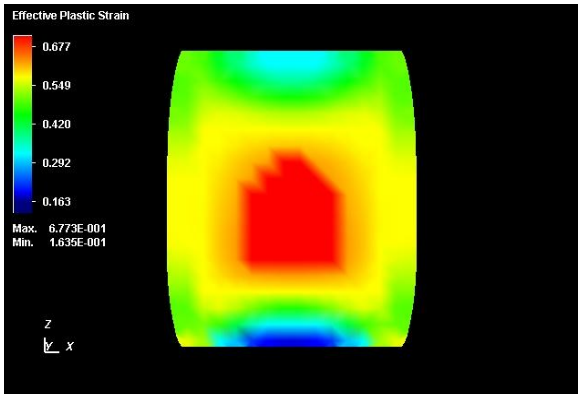
Optimization of Die Design for Forging a Turbo-Charger Impeller and a Ring Gear Using Process Simulation

Jay Gunasekera, PhD, DSc, PE, Professor of Mechanical Engineering, Ohio University, USA,
Mazyad Al-Moheib and Fahad Al-Mufadi, Former PhD students at Ohio University, USA

SYNOPSIS: The objective of this project was to optimize the preform and final die design for two complex automotive forged products (a turbine impeller and a ring gear) for two different forging companies in the US. The turbine impeller has to have a minimum effective plastic strain of 0.5 in order to increase the toughness and resist fracture due to the very high centrifugal stresses. It is also important to distribute the strain and the grain size as uniformly as possible throughout the finished forged part, so as to achieve the best mechanical properties for the Al 2618 turbine wheel. Optimization of grain size was performed by determining optimal temperature and average strain rate (by the use of Zener-Hollomon Parameter). The second project was to optimize the die design for a steel Ring Gear, so as to reduce the number of forging stages and also reduce the material wastage due to excessive flash. The software used was MSC.SuperForge, the predecessor of Simufact.forming, which is capable of checking the die filling, defect formation and die contact in the final stage. It can also determine and display a variety of useful parameters such as; the effective plastic strain, effective strain rate, effective stress, material flow, temperature, force-time relationship and final shape by using Superforge-FV (Finite Volume) simulation. It is concluded that the software can be effectively used to optimize the forging process to maximize the mechanical strength, minimize material scrap & forging stages and hence reduce the overall cost of manufacture.

1. INTRODUCTION:

The objective of this project was to optimize the preform and final die design for two complex automotive forged products. The first part is a turbo-charger impeller (or turbine wheel) made of aluminum. This part rotates at very high speed (up to 100,000 RPM), accelerates rapidly from rest and has very high centrifugal stresses. The new preform dies have to be designed, so that the effective plastic strain in the dead metal zone of this part can be increased to a value greater than 0.5. The yield strength can also be increased by the optimization of the new preform die design since it increases the low effective plastic strain in the dead metal zone. This also leads to a near uniform effective plastic strain throughout the formed product. Referring to Figure 1, it can be seen that a flat preform die was previously used in the forged rotating part with alloy AA2618. Referring to Figure 2, a die with the final contour was used to obtain an effective plastic strain greater than 0.5 in the final product. However, this does not result in an overall uniform plastic strain greater than 0.5. A problem associated with this product is the presence of low effective plastic strain which is displayed in Figures 1 and 2 by the regions of blue known as Dead Metal Zone (DMZ) [1].



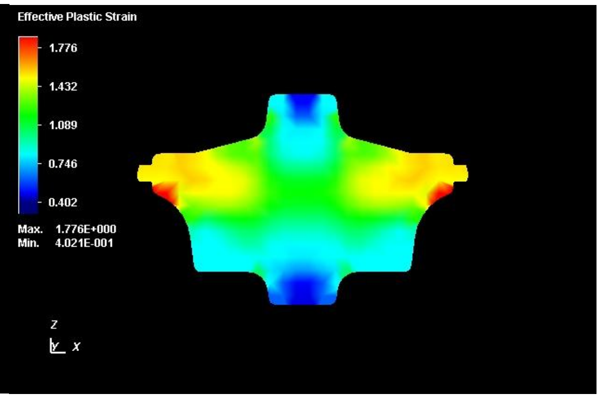


Figure 1 Strain contours with flat die   Figure 2 Final strain contours with flat die

The goal is to achieve the best mechanical properties throughout the forged rotating part made from AA 2618. The main advantage of the hot forging operation is gained by decreasing the inhomogenities of the workpiece; porosities are eliminated because of fusion of cavities. Another goal is the optimization of the Zener-Holloman parameter, Z, by determining an optimal temperature and an average strain rate, in order to get an indication of the grain size of the material. The Zener Holloman parameter increases with an increase in the average strain rate and the average strain rate increases with an increase in the effective plastic strain or decrease in forging time. It is also increased by a decrease in the forging temperature. The coarse columnar grains are replaced by smaller equiaxed, recrystallized grains that give an increase in ductility and toughness. This would decrease the strength in a direct forging, but, a preform where the magnitude of the strain has been increased would preserve the strength of the material.

The second part is a ring gear [2], and the objective here was to reduce the number of forging stages and also reduce any material wastage. 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 [3]. 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. Forging preform design is determined via backward deformation simulations using a procedure similar to die 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 important 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 favorable grain flow and the load required can be fulfilled by using adequate and appropriate pre-forms [3].

UBET (Upper Bound Element Technique) was used for the backward simulation to obtain an optimal perform and then Finite Volume Method (Simufact.forming software) was used to do the forward simulation and verify the design. UBET has been developed and used by many researchers; for example Lee et al. [4] used UBET to analyze the forging load, die filling, and the effective strain for forgings with and without flash gap. The program was 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. A pre-form design approach that incorporates both FEM-based forward simulations and UBET-based backward simulations was developed by Liu, et al. [5]. Bramley, [6], 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, et al. [7]. Finally, M. Mohelib and J.S. Gunasekera [8] used UBET for backward simulation in Ring Rolling and for forging a Ring Gear. The Ring Gear project is reported in this paper. The theory of UBET can be found in a number of excellent publications and will not be repeated here.

2. TURBINE WHEEL ANALYSIS [1]

The development of Finite Element Analysis (FEA) techniques has provided an important link between advances in die and equipment design and an improved understanding of materials behavior. Inputs to the FE codes include the characteristics of the work piece material (flow stress and thermal properties) and the tool/work piece interface (friction and heat transfer properties), as well as work piece and tooling geometries. Typical outputs include predictions for forming load, strain, strain rate and temperature contour plots, and tooling deflections. The method of study for this model is:

1. The models are first made in CAD software such as SOLID EDGE for the billets and for preform (upsetting dies) as well as closed die forging in both the upper and lower dies. This model is exported for three-dimensional FEA techniques such as FV (Finite Volume) analysis (simulation) of actual die forging of the rotating part with SUPERFORGE [9] to find flaws in the design of the preform.
2. To focus on optimizing the preform design.
3. To define the best preform design and finished work piece based on optimization results and to verify the applicability of this method.

One of the most important aspects of the closed-die forging process is the design of preforms (or blockers) to achieve adequate metal distribution. With the proper preform design, defect-free metal flow and complete die fill can be achieved in the final forging operation and metal losses into flash can be minimized. The determination of the preform configuration is an especially difficult task involving thorough metal flow understanding.

The 3D modeling software SolidEdge is used to model parts, billets and dies. SolidEdge has an option by which volume of the modeled part can be found. SolidEdge provides the option of Boolean operation by which a specific shape can be subtracted or added to another shape. For this research, lower-die and upper-die are modeled without Boolean operations. Simufact SUPERFORGE is used to simulate the forging process.

3. FINITE VOLUME METHOD

The traditional finite element mesh distorts when an effort is made to track the deformation of the material. However, when the finite volume method is used, the computational mesh uses a finite volume mesh with an unchanging frame of reference when the material of the billet flows through the mesh. The energy, the mass and the momentum of the material are transported from one component to another. The grid points for the finite volume solver are preset in space and the elements are just partitions of the space defined by the connected grid points. The material of the billet beneath analysis moves throughout the finite volume mesh. Thus, the movement of the material via the elements of constant volume is computed by the finite volume solver. The dies work like a boundary to the flow of material in a forging simulation employing the finite volume mesh, where as the stresses present in the material contained by the finite volume mesh apply forces on the surfaces of the dies. In the finite volume technique, the mesh must be big enough to cover the material of the work piece once deformation has taken place. A fundamental finite element mesh also acts like a container and the material cannot depart the mesh. From a finite volume mesh, stress wave reflections and pressure buildup develop, but are not significant enough to be analyzed. FVM computer modeling is favorable for simulating gross material deformations intrinsic in forging operations due to this distinctive feature. Moreover, the requirement for remeshing techniques which are usually thought to be the major bottlenecks in 3-D forging simulations based on the finite element method, is totally eliminated [9,10].

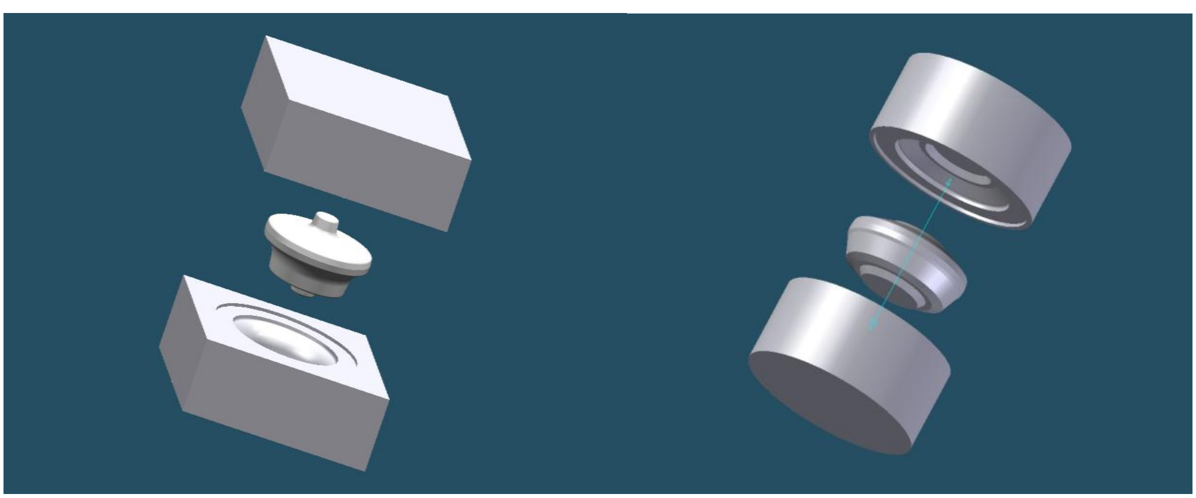
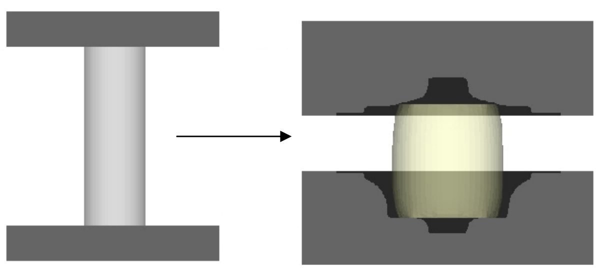
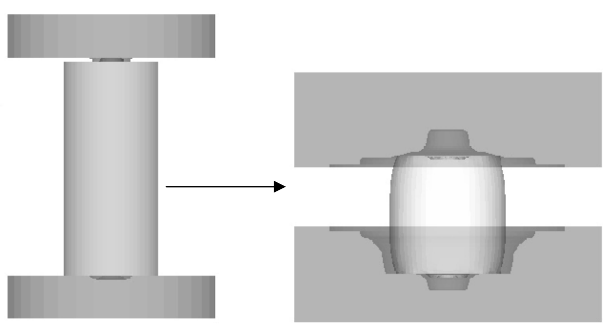


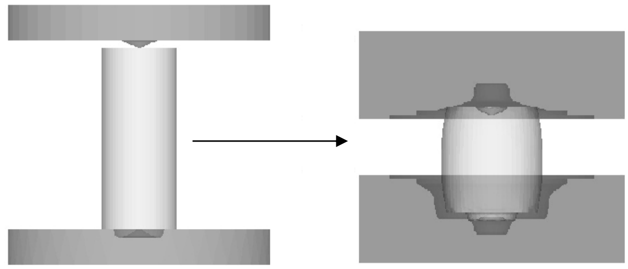
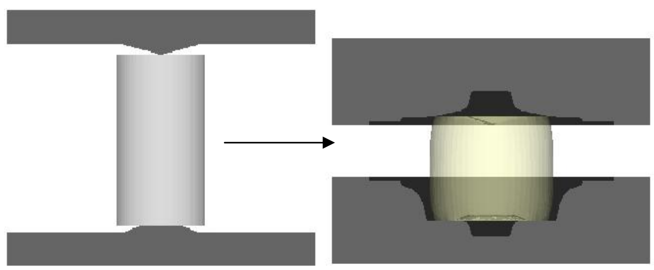
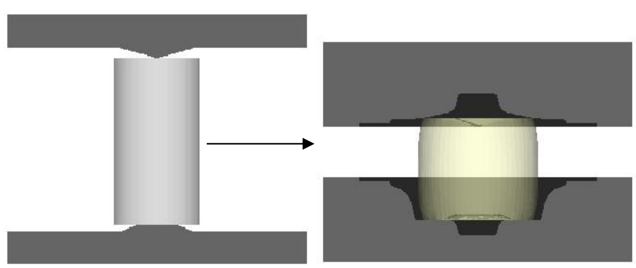
Figure 3 Model of upper dies, lower dies and billets

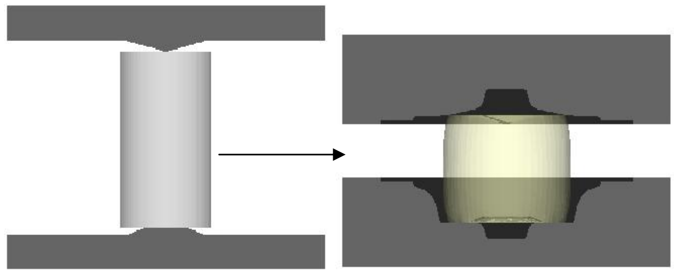
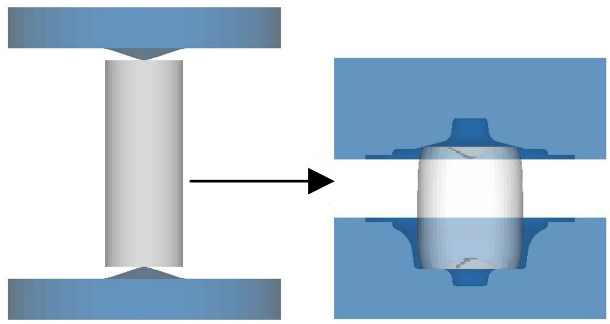
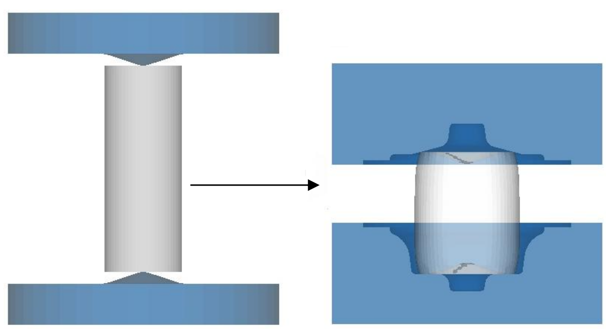
It is important to understand the effect of different preform designs for the minimum effective plastic strain, and the comparison of range of values in order to determine the uniformity of the effective plastic strain in the work piece. Ten geometrically differing preform dies were designed to analyze the effective plastic strain in the workpiece with the objective being to find the highest value for minimum effective plastic strain and also the minimum range (difference between maximum and minimum) for effective plastic strain. This minimum range indicates the most uniform effective plastic strain for a particular preform.

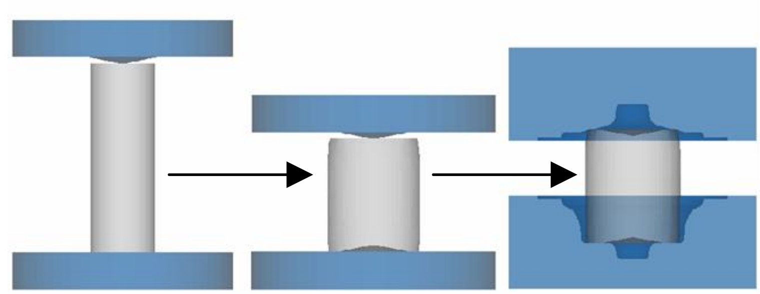
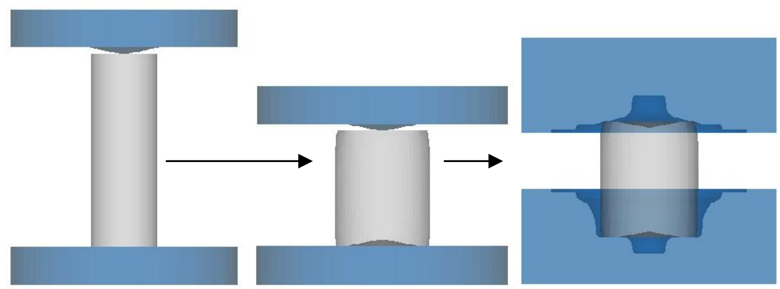
Table 1 shows the ten different geometries of the die designs used. The design of the preform with the best geometry helps to increase the minimum effective plastic strain and also creates uniformity in the workpiece. The best designs had a conical protrusion in the perform die to penetrate the dead metal zone (DMZ).

Table 1: Preform design for all test cases

Case #	**Description**	**Design**
1	Flat preform die	
2	Preform flat upper die with protruding ring and preform flat lower die with an engraved ring	

3	Preform flat upper die with protruding cone and preform flat lower die with an engraved cone	
4	Preform flat upper die with a 12° base angle protruding cone and preform flat lower die with a 43° base angle frustum of a circular cone	
5	Preform flat upper die with a 18° base angle protruding cone and preform flat lower die with a 43° base angle frustum of a circular cone	

6	Preform flat upper die with an 26° base angle protruding cone and preform flat lower die with a 43° base angle frustum of a circular cone	
7	Single stage preform flat upper and lower dies with a 10° base angle protruding cones	
8	Preform flat upper and lower dies with an 18° base angle protruding cones	
9	Two stage	

	preform flat lower die and upper die with a 10° base angle protruding cone	
10	Two stage preform flat lower die and upper die with an 18° base angle protruding cone	

Data obtained for the effective plastic strain for maximum, minimum, and range of difference is shown in Table 2. This data was collected after simulating the ten different kinds of preform die designs which can be seen in Table 1. Die temperatures, billet temperatures, and interface friction factor were fixed for all cases. The work piece temperature was 425 C, initial die temperature 250 C, and friction factor was 0.8.

Table 2: Values of effective plastic strain obtained by change in preform die design

	Maximum	**Minimum**	**Range of difference**	**Av.**
Preform 1	1.776	0.402	1.374	1.089
Preform 2	1.722	0.384	1.338	1.053
Preform 3	1.745	0.533	1.212	1.139
Preform 4	1.795	0.681	1.114	1.238
Preform 5	1.802	0.682	1.120	1.203

Preform 6	2.031	0.685	1.346	1.358
Preform 7	1.717	0.782	0.935	1.249
Preform 8	1.737	0.79	0.947	1.263
Preform 9	1.792	0.732	1.060	1.262
Preform 10	1.744	0.782	0.962	1.263

Ten different preforms were designed and analyzed to obtain the final product in one and two preform stages. From this study, it can be concluded that the two stage preform with a flat lower die and an upper die with a 10° base angle protruding cone is best in terms of increasing the minimum effective plastic strain for uniform distribution and filling the dies in the final stage. After studying different combinations of workpiece temperature, die temperature, and friction factor, the following values were found to be the most optimal: work-piece temperature 425 C, die temperature 250 C, and interface friction factor of 0.3. An optimal average strain and the highest minimum strain were calculated for these values. The final simulation results are shown in Figure 4.

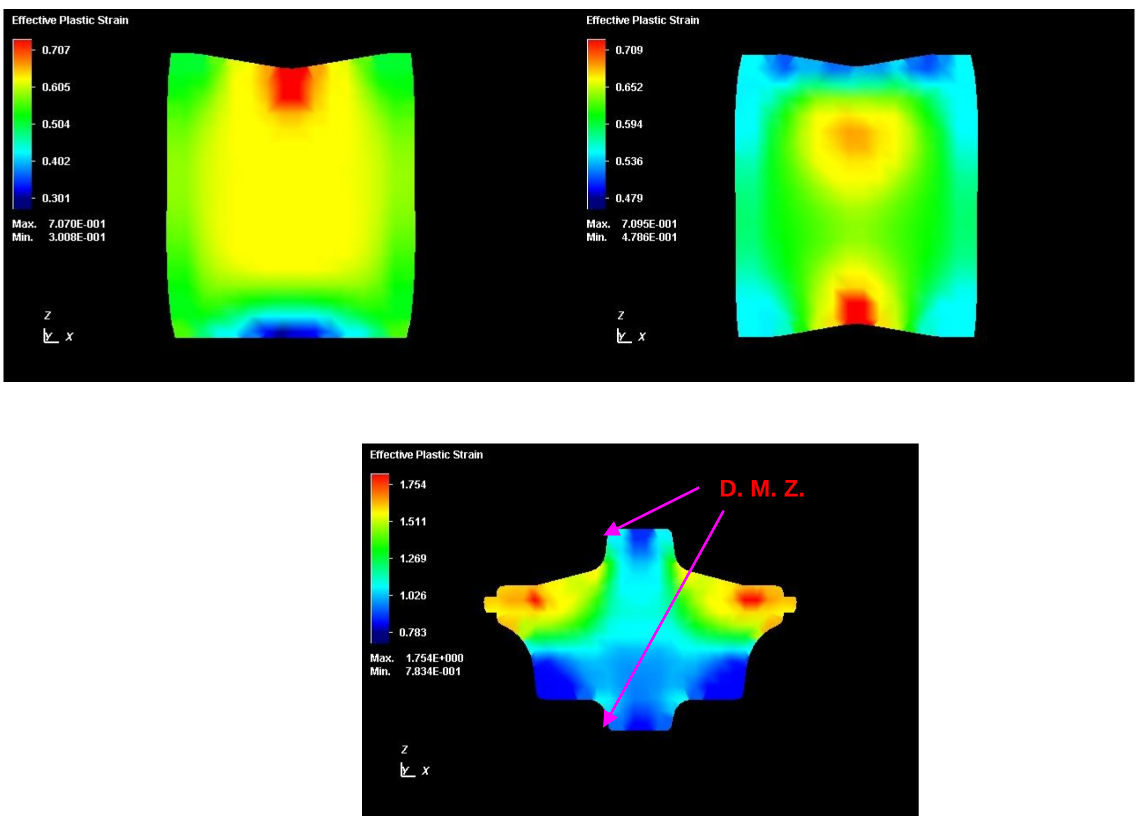


Figure 4: Effective Plastic Strain using preform with cone angle 10°

The three images correspond to the first stage preform, the second stage preform, and the shape obtained in the final stage. The arrows in the final shape image point to the minimum effective plastic strain which is present in the dead metal zone areas, but they are all over 0.75 effective strain.

The Zener-Holloman parameter was calculated and is shown in Figure 5. Good values were obtained for the Zener-Holloman parameter as the parameter was uniform and the range of difference was not too high. This is so because; the power of both the lower and upper values for Z is the same; $1.87 \times 10^{12} \leq Z \leq 3.48 \times 10^{12}$. Zener-Holloman parameter is defined as;

$$Z = \dot{\varepsilon} \exp\left(\frac{Q}{RT}\right)$$

In the above expression, Q is the activation energy for deformation, 161kJ/mole, R is the universal gas constant, 8.314 J/mole-K, and T is the absolute temperature.

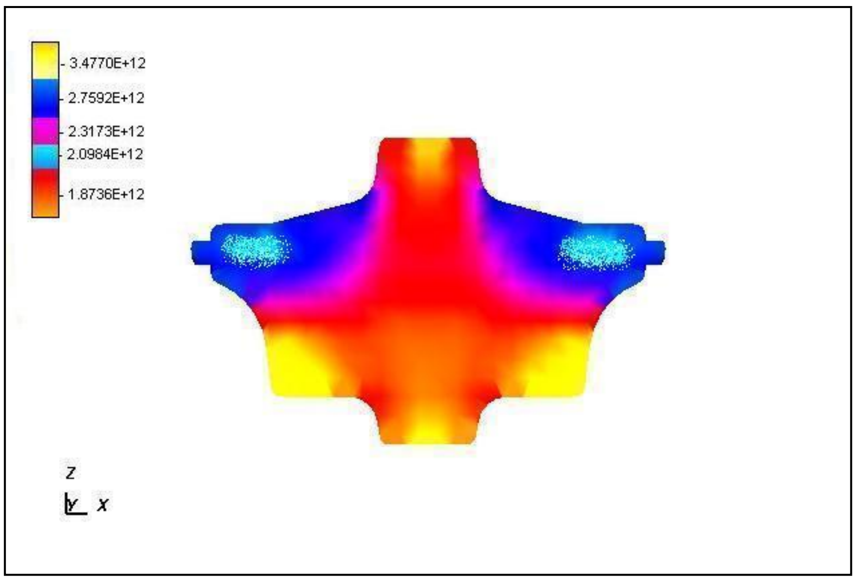


Figure 5: Zener Hollomon parameter

4. VALIDATION OF RESULTS

To substantiate the research work carried out, the experimental results were compared to the ones obtained by simulation. This comparison displayed the accuracy of the research work and, hence, validated the research. The dies were industrially fabricated for experimental work, which has been done in order to compare it with the simulation. The dimensions of the work piece and the filling of the die in the simulation were compared with the results of the actual experiment. (The experimental work was carried out to validate the computed results of the forging simulation using the Finite Volume method.)

It is important to compare the dimensions of the part, obtained by simulation with that of actual experimentation, in order to see how good the results are. An actual product was obtained after the experimental work was carried out for all the three stages of the part forging. Analysis through simulation is beneficial in many ways. Real-time results can be obtained in the simulation without actual experimentation. Simulation also reduces various experimental costs, saves money on materials, and eliminates valuable experimentation time. (All the experiments-actual forgings were done at the Queen City Forging Co).

Figure 6: Results obtained for the preform and final stages in the industry

The results obtained by experimentation are closely confirmed by those obtained by simulation, hence, validating the theoretical part forging obtained by the Finite Volume Method. The percentage error between the Finite Volume Method simulation results and the experimental results in relation to matching the heights and diameters has been found to lie in the range of 1.311 % - 8.055 % in the perform stage and 0.030 % - 6.019 % in the final stage . Thus, the Finite Volume Method simulation results closely resembled with the experimental results. The error present may have been due to the size of the elements in the edges and corner or due to possible manual error during the experimental work. Consequently, the Finite Volume Method appears to be a good method for the simulation of forging in the preform and final shape.

5. RING GEAR ANALYSIS [2]

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 7) 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.

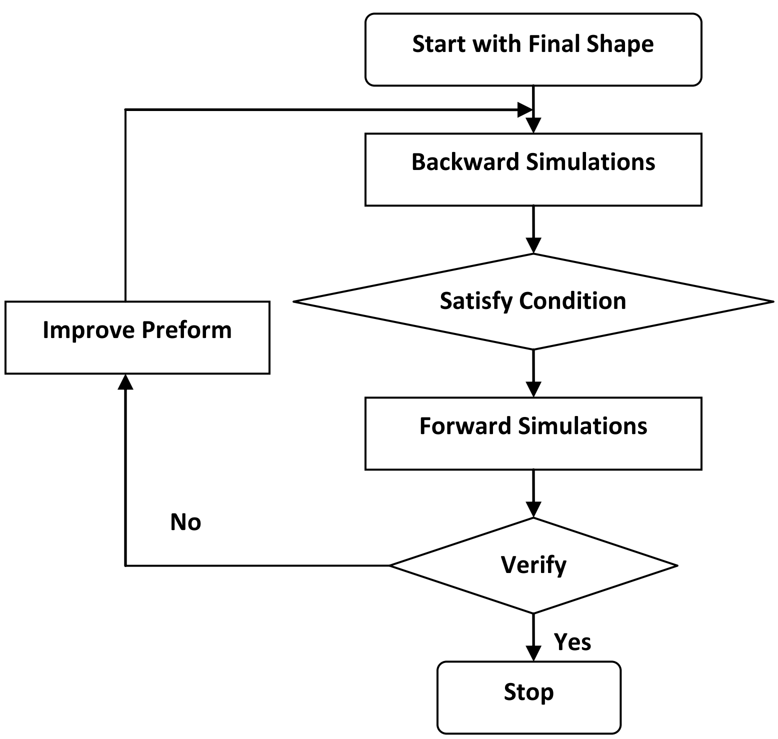


Figure 7. Flow chart of the forging preform design process [2]

6. RESULTS AND 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 Simufact.forming 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 material used was steel AISI-4337 and was performed at temperature of 2100^{o} F and then reduced to about 1800^{o}F. The preform obtained by volume mapping approach (Figure 8) is verified by conducting forward computer simulations using SIMUFACT.FORMING.

Several forward computer simulations including 2D (axisymmetric) 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. 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 (case--1) with 10% volume reduction as shown in Figure 9.

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 2D and 3D for the net shape forging (case--2) are shown in Figure 10 and Figure11 respectively, also the lower dies for both stages (case--3) were modeled with circular pockets so that the operators can position the workpiece at the center of the lower dies as shown in Figure 12.

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.

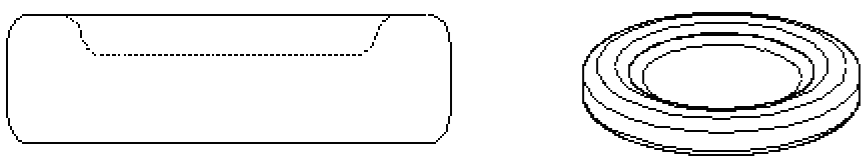


Figure 8. Preform obtained by volume mapping approach

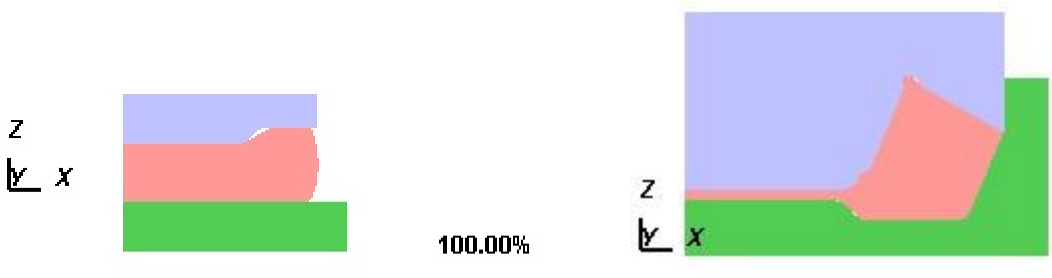


Figure 9: Precision flash-less forging (case--1)

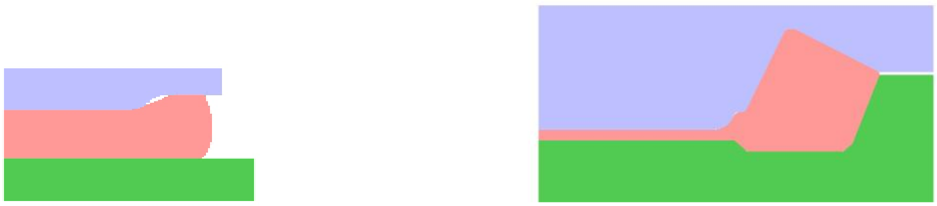


Figure 10. Net shape forging (case--2) 2D simulations

Figure 11. Net shape forging (case--2) 3D simulations

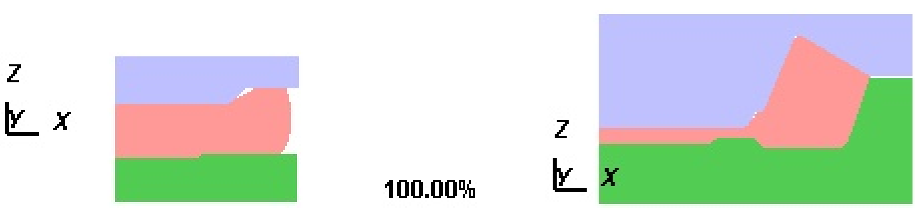


Figure 12. Net shape forging using centered lower die (case--3)

7. CONCLUSIONS:

In this research, the development of a volume mapping technique to arrive at an optimum preform/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 (using SIMUFACT.FORMING) 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, and the final shape of the ring gear blank was achieved with complete die fill using the preforms obtained by volume mapping approach.
- The initial billet temperature can be reduced to 1800^{o} F.
- The final stage can be carried out using flash-less precision forging in which the material wastage can be reduced to about 10%.
- 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. This 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.

8. ACKNOWLEGEMENTS

The authors wish to thank Queen City Forging Co., American Axle & Manufacturing Inc. and Forging Industry Association-FIERF for their technical and financial support to conduct these research projects. Both the former PhD students obtained their PhDs at Ohio University and are now Professors in two Universities in Saudi Arabia-address not known.

9. REFERENCES

1. Fahad Al-Mufadi, Optimization of a New Preform Die Design for Forging a Rotating Part using Computer Modeling and Analysis, PhD, Ohio University June 2004

2. Mazyad M. Al-Mohaileb, Computer Modeling of Complex Metal Forming Processes using the Upper Bpund Elemental Technique (UBET), PhD, Ohio University Oct. 2003

3. Altan, T., Oh, S., Gegel, H., Metal Forming Fundamentals and Applications, American Society for Metals, 1995.
4. 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.
5. 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
6. Bramley A., N., "UBET and TEUBA: Fast Methods for Forging Simulation and Preform Design" *Journal of Material Processing Technology* 116 (2001) 62-66
7. 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
8. Mazyad Almohaileb and Jay Gunasekera, Modeling of Profile Ring Rolling using the Modified Upper Bound Elemental Technique, *Intl Conf on Advances in Materials and processing Technologies,* July 30-Aug 3, 2006, Las Vegas, NV
9. MSC/Super Forge User's Manual (Version 1.0), The MacNeal- Schwendler Corporation, 1998 (now replaced by Simufact.forming software).