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# Preform Shape Optimization for Manufacturing a Constant Mesh Gear by a Closed Die Hot Forging Process using Simulation Techniques

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Abstract: **In this research, efforts have been made to design preform shape for constant mesh gear in order to ensure complete filling of the material in die cavity during closed die forging. There are eight different preform types tested using simulation technique based on finite element method. On the basis of findings of this study, the best preform for near-net-shape gear-forging are suggested. This investigation helped in successfully creating a high-quality preform with uniform and fine microstructure. This is achieved by using an optimized billet with the correct initial shape, acquired through a systematic reverse optimization method that avoided common issues like underfilling, excessive flash generation and folding during preforming. The experiments are simulated using the optimized initial billet, and the results are found to be reasonable and reliable. In the current situation, when there is a lot of emphasis on correct design in a short amount of time, such a study to determine optimum preform shape has a lot of industrial value.**

***Keywords —Closed Die Hot Forging, Preform, FEA, Simulation, Manufacturing, Constant Mesh Gear, Automobile, Optimization***

## I. INTRODUCTION

During the forging process, a block of metal called a billet is compressed between two or more dies to create a complex part. The shape of the initial billet is very important for achieving the desired characteristics in the final forged part. Conventionally, an experienced designer would rely on their expertise and design data handbooks to optimize the billet shape. However, with the development of better computers, more advanced shape optimization techniques have been created and are now being used in various industries. These techniques are more efficient and reliable than traditional methods.

In the metal forming process, net shape forging means forging components to their final dimensions with no additional machining required. Near-net-shape forging, however, means forging the components as close as possible to the final dimensions, with minimal machining or grinding needed after forging and heat treatment. The automotive industry is the main customer of net shape forging companies, and they require fast delivery, low costs, and high quality. Suppliers face challenges of producing smaller batch sizes and a wider variety of part types. Automobile manufacturers prefer parts that require minimal machining or can be assembled directly. Net shape hot forging parts meet these requirements.

The authors [1] focus on finding the optimal shape of an initial billet for preforming TA15 Ti-Alloy complex components. The authors used a combination of simulation and optimization techniques to determine the best shape for the billet. The results showed that the optimized billet shape leads to improved material utilization and better mechanical properties in the final components. Overall, the study provides valuable insights for manufacturers seeking to improve the preforming process for TA15 Ti-Alloy components. Multi-level design process for optimizing the 3-D preform shape in metal forming – A new approach that involves multiple levels of optimization, each one building on the results of the previous one is proposed by the authors [2]. The results show that this multi-level approach leads to improved preform shapes and better metal forming outcomes. The study is well-conducted, and the results are supported by relevant data and experiments. Overall, this research provides valuable information for engineers and manufacturers looking to improve the metal forming process. The optimization of the shape of a workpiece in the forging process through the use of equivalent static loads investigated by authors [3]. The authors use numerical simulations and optimization algorithms to determine the optimal shape. The results demonstrate that this approach results in improved forging outcomes such as reduced deformation and enhanced surface quality. This study

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provides valuable data for those in the manufacturing industry who are looking to optimize the forging process and produce high-quality workpieces. The authors' approach shows a significant contribution to the field of forging optimization. The Optimization of billet shape for minimum forging load using finite element analysis (FEA) is demonstrated by the authors [4]. The focus of the research was to minimize the forging load while maintaining the desired final shape of the workpiece. The methodology involved using FEA simulations to analyze the impact of different billet shapes on the forging load. The results showed that the optimization of billet shape resulted in a significant reduction in the forging load without sacrificing the final shape quality. The uniqueness of the research lies in the use of FEM analysis for billet shape optimization, which provides a more accurate and comprehensive understanding of the forging process compared to traditional methods. The results of the research provide a practical solution for reducing the forging load in the industry, making it a valuable contribution to the field. This work provides a thorough and well-executed investigation into the topic of optimizing billet shape for least forging load. The authors [5] concentrates on the optimization of the shape and preform design in metal forming processes. The aim of the research is to improve the efficiency and effectiveness of the metal forming process. The methodology used in the research includes mathematical modelling, simulations, and experiments. The results of the research show that the proposed shape optimization and preform design techniques result in improved product quality and reduced production costs. The significant aspect of the study is that it provides a thorough understanding of the metal forming process by combining mathematical modelling with real trials. The shape optimization of preform for selected gear is targeted by the authors [6]. The aim was to select optimal preform shape which gives near net shape forging from selected four preform shapes by comparing the results obtained at the end. The methodology involved using numerical simulations in SIMUFACT Forming Software. Parameters such as Effective Stress, Effective Strain and Applied Forces were compared for all four preform shapes. The results showed that only one preform leads to the near net shape forging. The present study offers a significant addition into the optimization of preform design and will be of interest to those in the field of materials science and engineering.

The aim of this research is to provide the optimal preform shape for near net shape forging. The optimal preform shape should provide following:

1. complete filling of the finish die impression with the minimum material loss to flash,
2. lower forging load,
3. minimized die wear and
4. no flow defects like laps or flow-through defects.

## II. GEOMETRY

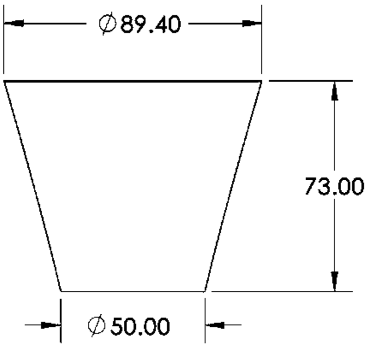

Fig.1 – Conical Frustrum Shape Preform with Large Top (Case 1)

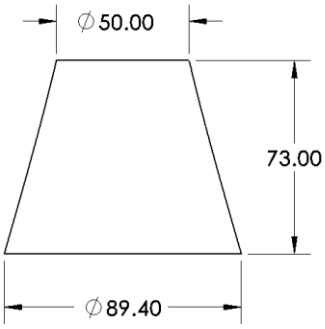

Fig.2 – Conical Frustrum Shape Preform with Large Bottom (Case 2)

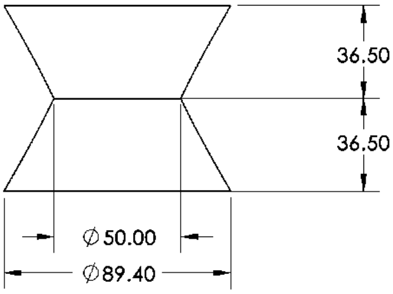

Fig.3 –Inverted Double Frustrum Shape Preform (Case 3)

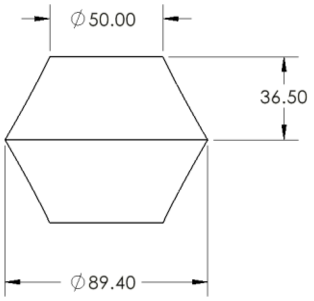

Fig.4 – Double Frustrum Shape Preform (Case 4)

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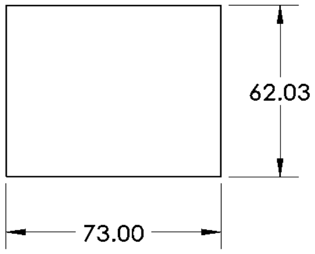

Fig.5 –Horizontal Rectangular Shape Preform (Case 5)

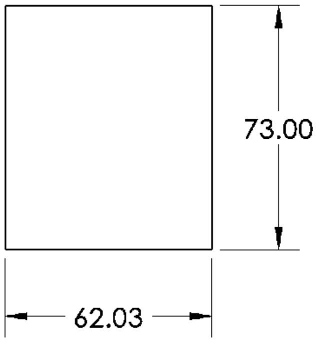

Fig.6 –Vertical Rectangular Shape Preform (Case 6)

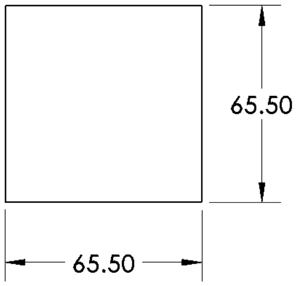

Fig.7 –Square Shape Preform (Case 7)

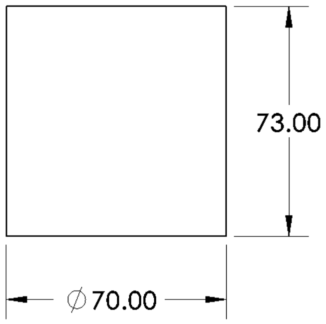

Fig.8 –Cylindrical Shape Preform (Case 8)

Note: All dimensions are in mm.

In the present study, billets of different shapes as shown in Fig. 1 to Fig. 8 have been considered. Conical Frustrum Shape preform with large top (Case 1) has 44.7 mm radius at the top and 25 mm radius at the bottom and height of 73 mm as shown in Fig.1. Conical Frustrum Shape preform with large bottom (Case 2) has 25 mm radius at the top and 44.7 mm radius at the bottom and height of 73 mm as shown in Fig.2. Inverted Double Frustrum Shape Preform (Case 3) has 25mm radius at the middle & 44.7 mm radius at top and bottom as shown in Fig.3. Double Frustrum Shape Preform (Case 4) has 44.7 mm radius at the middle and has 25 mm radius at top and bottom as shown in Fig.4. Horizontal Rectangular Shape Preform has length of 73 mm, height of 62.03 mm and width of 62.03 mm as shown in Fig.5. Vertical Rectangular Shape Preform has length of 62.03 mm, height of 73 mm and width of 62.03 mm as shown in Fig.6. Square Shape Preform has length, height and width of 62.03 mm as shown in Fig.7. Cylindrical Shape Preform has radius of 70 mm and height of 73 mm as shown in Fig.8. All these preform were tested and their results were compared.

## III. MATERIALS

20MnCr5 is utilised in the production of constant mesh gear. 20MnCr5 steel is a common alloy of chromium and magnesium. It is a low-alloyed case-hardening engineering steel. It is used for shafts, gears, camshafts, spindles, piston bolts, and other mechanical control components. It is a low-alloy steel with a hardness range of HRC 41. This material has a robust core and can be carburized or carbonitrided to provide a durable casing. Power Transmission components such as Spur gears and helical gears that require low to no size change during heat treatment and no post-heat treatment finishing operations would benefit from the use of this alloy.

**PROPERTIES OF 20MnCr5:**

Minimum temperature: 1173.15 K

Maximum temperature: 1523.15 K

Minimum effective plastic strain: 0.05

Maximum effective plastic strain: 2.0

Minimum strain rate: 0.01 1/s

Maximum strain rate: 150.0 1/s

Yield strength: Constant: 6.3032e+7 Pa

Chemical Composition of 20MnCr5:

**Table 1.** Chemical Composition of 20MnCr5

| Element | C | Si | Mn | P | S | Cr |
|---|---|---|---|---|---|---|
| Wt% | 0.17-0.22 | max 0.4 | 1.1-1.4 | max 0.035 | max 0.035 | 1-1.3 |

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## IV. METHODOLOGY

In this research, close die forging of a constant mesh gear has been carried out. Fig.9 depicts the machine drawing of the considered component. Fig.10 depicts a 3D model with several view-points. Pictures depicting selected gear component is shown in Fig.11. As mentioned earlier, the aim of this study is to find out preform for near-net-shape of gear component. To achieved this goal following eight types of preforms are considered:

Case 1: Conical Frustrum Shape preform with large top

Case 2: Conical Frustrum Shape preform with large bottom

Case 3: Inverted Double Frustrum shape preform

Case 4: Double Frustrum shape preform

Case 5: Horizontal Rectangular shape preform

Case 6: Vertical Rectangular shape preform

Case 7: Square shape preform

Case 8: Cylinder Shape preform

Here, it is important to note that the volume of all these eight preforms is maintained exactly the same **280.608 $cm^3$** for this study.

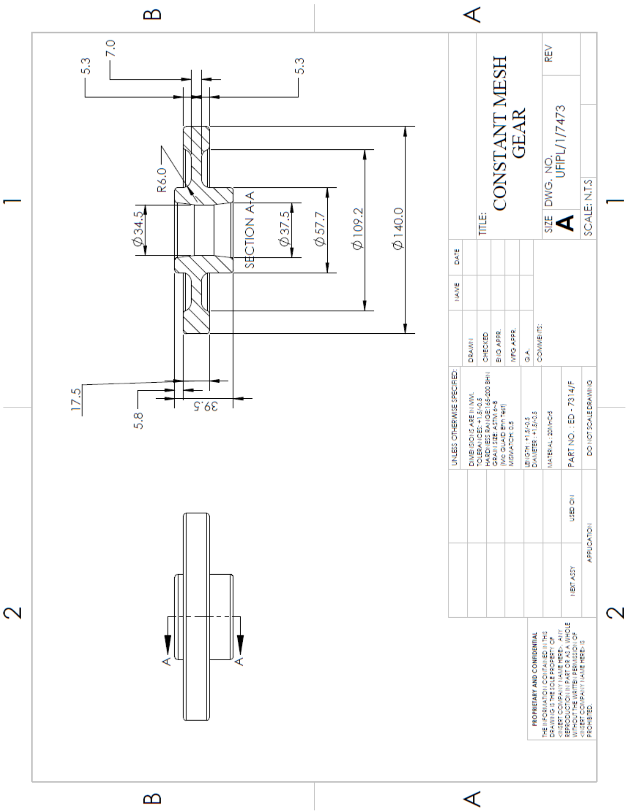

Fig. 9. Forging Drawing of the Constant Mesh Gear

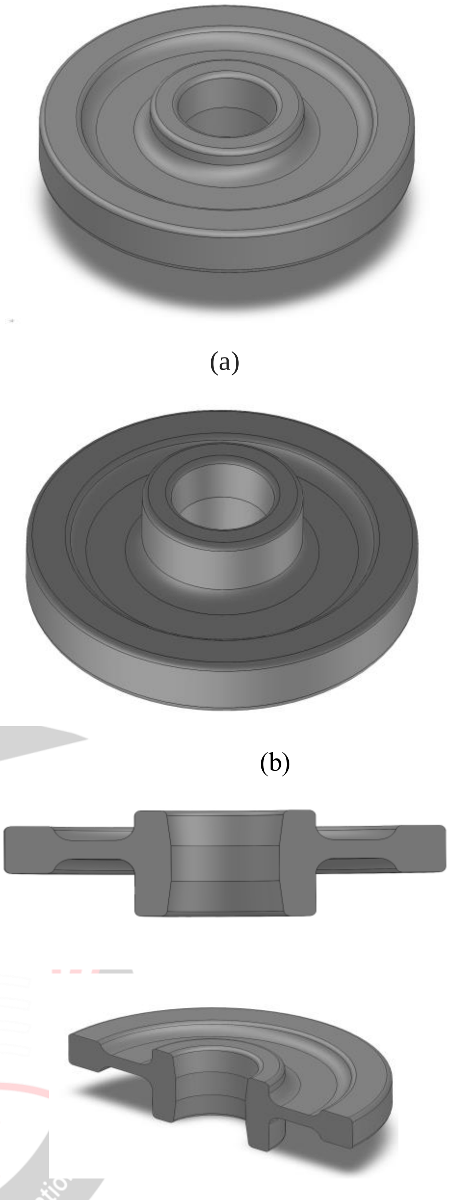

Fig. 10. Different View Points of 3D Model: (a) Isometric View; (b) Rear View; (c)Section View.

(a)

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(b)

Fig. 11. Selected Gear: (a) Top View (b) Bottom View

The following are the four stages involved in the forming process simulation.

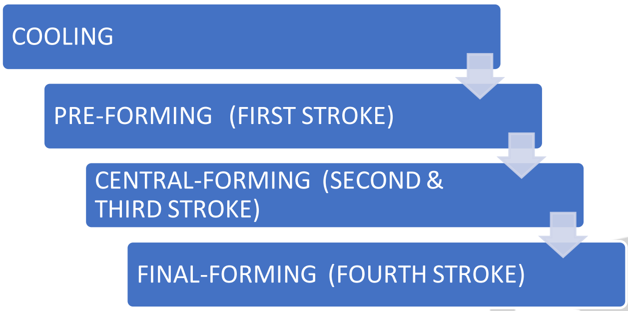

**Fig.12** – Stages of Forging Process Simulation

The specifications of various inputs required for simulation are as follows:

**(A) MATERIAL DEFINITION:**

Material Designation (For Billet): 20MnCr5 (AISI 5120)
Size of the Billet: ϕ 70 × 73
Input Billet Temperature: 1100 °C

**(B) TOOLING DEFINITION:**

Material Designation (For Die): AISI H13
Die Preheating Temperature: 350 °C
Dimensions of the Die: 360 × 360 × 220 mm

**(C) MESHING INFORMATION:**

Element Shape: Tetrahedron
Element Size: 3 mm
Mesh Type: Volume Mesh

**(D) MACHINE SPECIFICATION:**

Type of Machine: Mechanical Crack Press
Maximum Capacity: 8000 T
Connecting Rod Length: 1500 mm
Crack Radius: 200 mm
Revolutions: 35 RPM

**(E) BOUNDARY CONDITIONS:**

Environmental Temperature: 35°C
Co-efficient of Friction: 0.3
Heat Transfer Co-efficient: 11 N/sec/mm/ ° C
Convection Co-efficient: 0.02 N/sec/mm/ ° C

## V. RESULTS AND DISCUSSION

### CASE: 1 – Conical Frustrum Shape Preform with Large Top

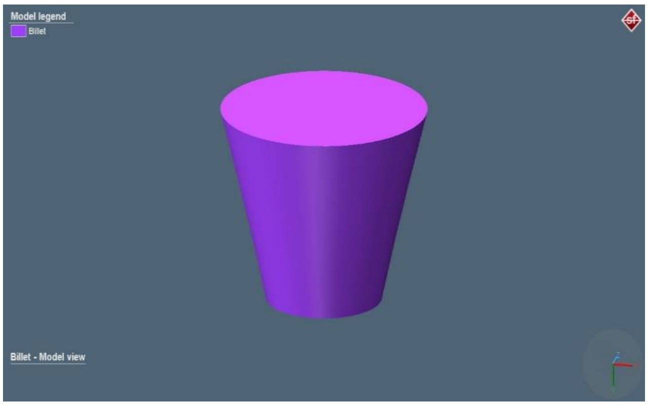

Fig.13- Conical Frustrum Shape Preform with Large Top

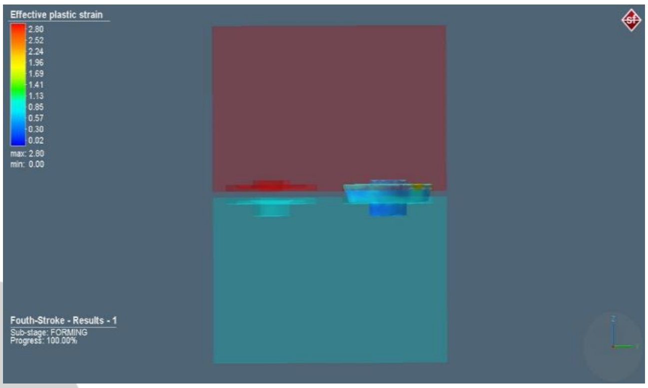

Fig.14: Transparent view after simulation (Case 1)

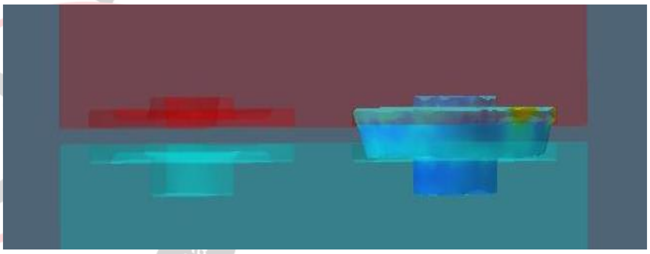

Fig.15: Magnified Transparent view after simulation (Case 1)

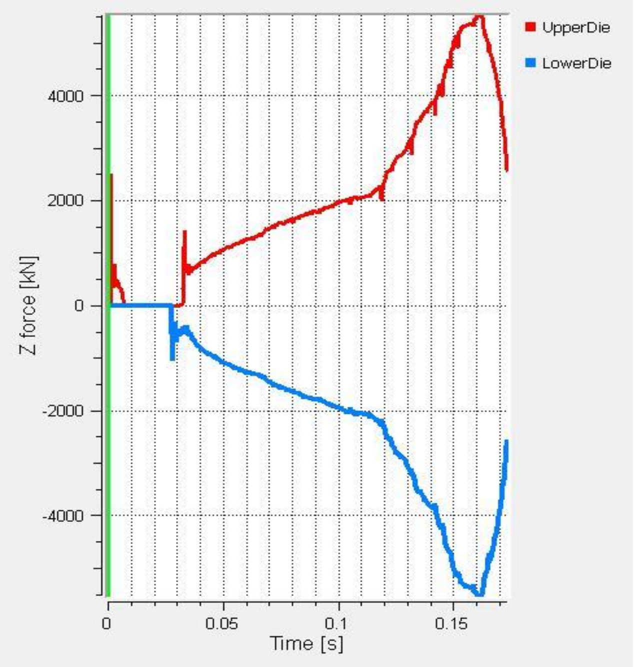

Fig.16: Die Force Variation in Both Dies (Case 1)

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3D model of billet considered in case 1 is shown in Fig.13. Whereas, transparent views of billet are shown in Fig.14 and Fig.15. After simulation it has been found that maximum plastic strain act on billet is 2.80. Maximum effective stress is 236.06 MPa. Maximum Die wear in Upper Die has been found as 2.83E-11 mm. Maximum Die wear in Lower Die has been found as 9.73E-12 mm. Maximum Temperature on final forged is 1136.14°C. Maximum Strain rate in final forged part is 11.90 1/s. Average of Maximum force experienced by both dies has been found as 5515 kN and for this preform, Die Force variation in both dies is shown in Fig.16. It can be observed that material does not enter in the die cavity completely due to this gear has not formed with desired shape and dimensions. Hence this perform is not suitable for net shape forging. Here, it is important to note that complete filling of Die Cavity does not means cavity of both dies fill completely. Complete filling of Die Cavity means Material Should be spread uniformly across both the dies with letting equal amount of space at outside edge for safely removal of final forged part from cavity and giving us the desired shape and dimensions.

### CASE :2 – Conical Frustrum Shape Preform with Large Bottom

Fig.17- Conical Frustrum Shape Preform with Large Bottom

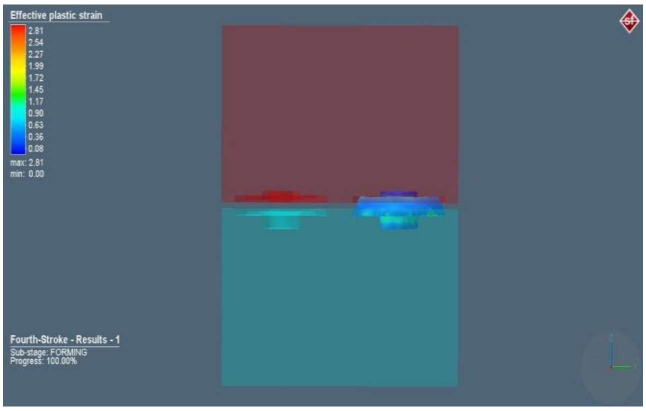

Fig.18: Transparent view after simulation (Case 2)

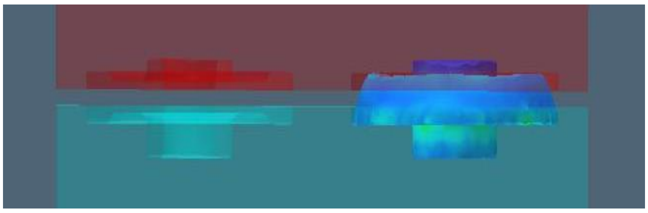

Fig.19: Magnified Transparent view after simulation (Case 2)

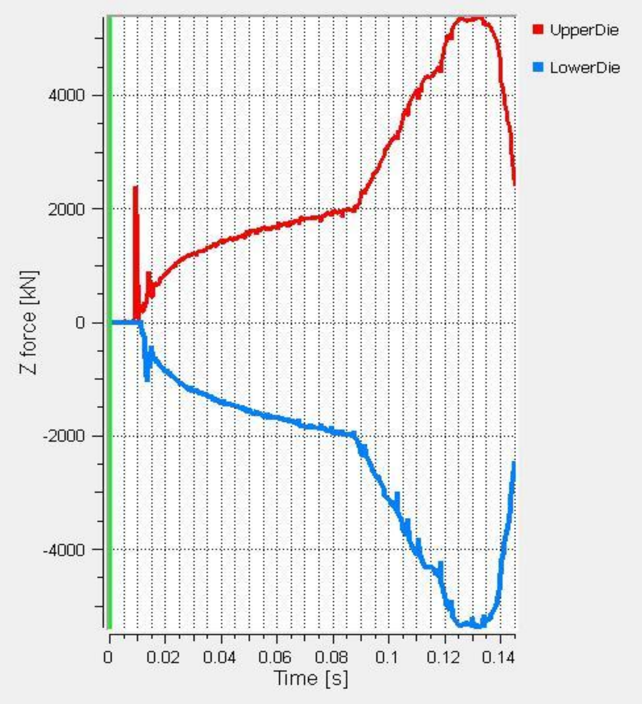

Fig.20: Die Force Variation in Both Dies (Case 2)

3D model of billet considered in case 2 is shown in Fig.17. Whereas, transparent views of billet are shown in Fig.18 and Fig.19.After simulation it has been found that maximum plastic strain act on billet is 2.81. Maximum effective stress is 237.40 MPa. Maximum Die wear in Upper Die has been found as 2.76E-11 mm. Maximum Die wear in Lower Die has been found as 9.49E-12 mm. Maximum Temperature on final forged is 1818.57°C. Maximum Strain rate in final forged part is 12.10 1/s. Average of Maximum force experienced by both dies has been found as 5380 kN and for this preform, Die Force variation in both dies is shown in Fig.20. It can be observed that material does not enter in the die cavity completely due to this gear has not formed with desired shape and dimensions. Hence this perform is not suitable for net shape forging.

### CASE: 3 – Inverted Double Frustrum Shape Preform

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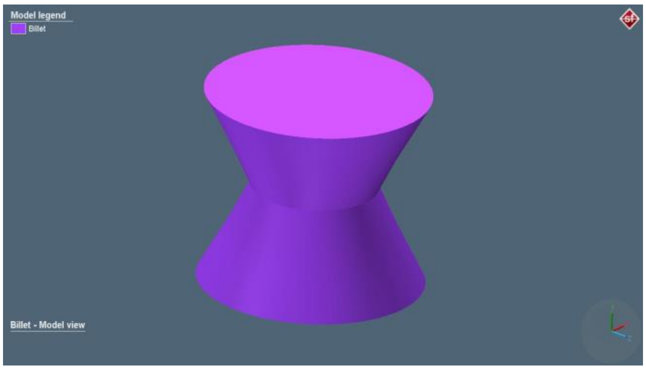

Fig.21- Inverted Double Frustrum Shape Preform

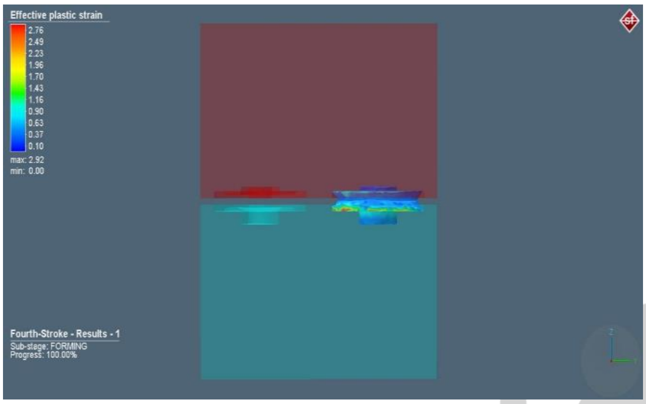

Fig.22: Transparent view after simulation (Case 3)

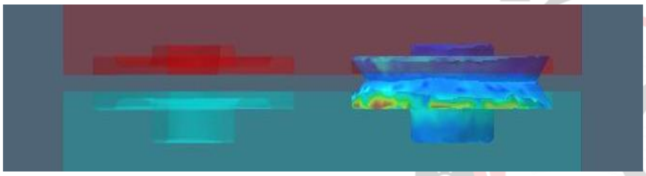

Fig.23: Magnified Transparent view after simulation (Case 3)

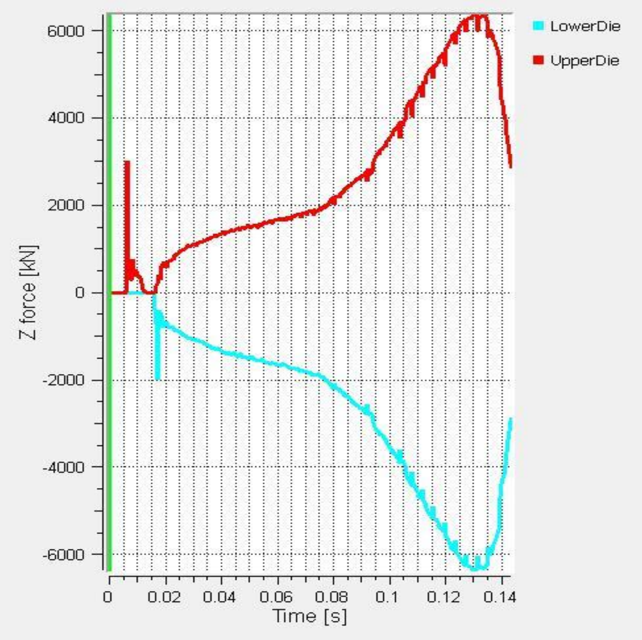

Fig.24: Die Force Variation in Both Dies (Case 3)

3D model of billet considered in case 3 is shown in Fig.21. Whereas, transparent views of billet are shown in Fig.22 and Fig.23.After simulation it has been found that maximum plastic strain act on billet is 2.76. Maximum effective stress is 232.70 MPa.Maximum Die wear in Upper Die has been found as 3.28E-11 mm. Maximum Die wear in Lower Die has been found as 1.12E-11 mm. Maximum Temperature on final forged is 1785.23°C. Maximum Strain rate in final forged part is 11.74 1/s. Average of Maximum force experienced by both dies has been found as 6354 kN and for this preform, Die Force variation in both dies is shown in Fig.24. It can be observed that material does not enter in the die cavity completely due to this gear has not formed with desired shape and dimensions. Hence this perform is not suitable for net shape forging.

### CASE: 4 – Double Frustrum Shape Preform

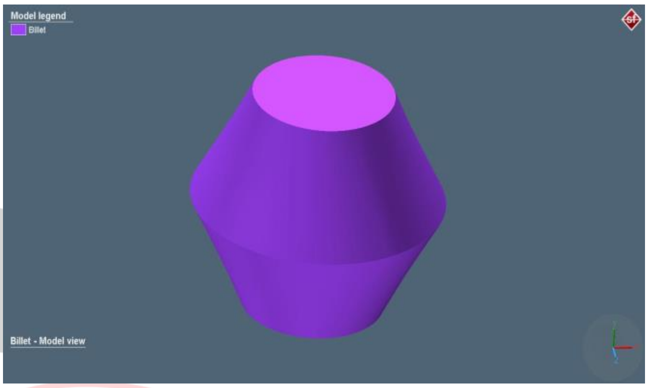

Fig.25- Double Frustrum Shape Preform

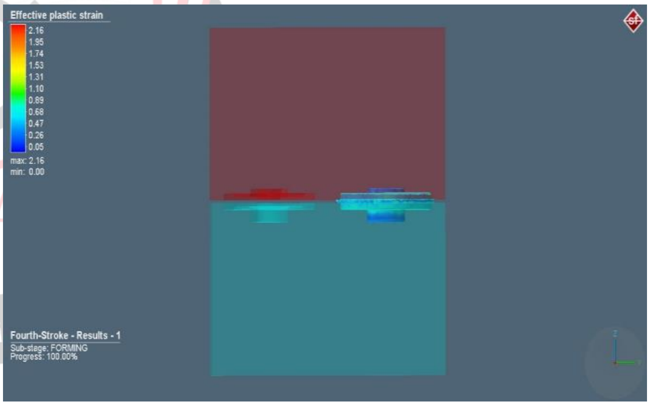

Fig.26: Transparent view after simulation (Case 4)

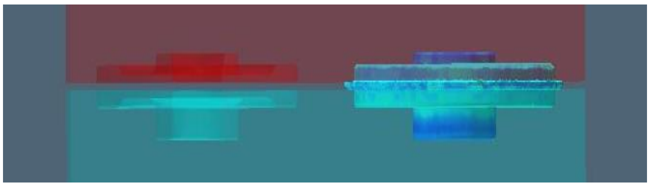

Fig.27: Magnified Transparent view after simulation (Case 4)

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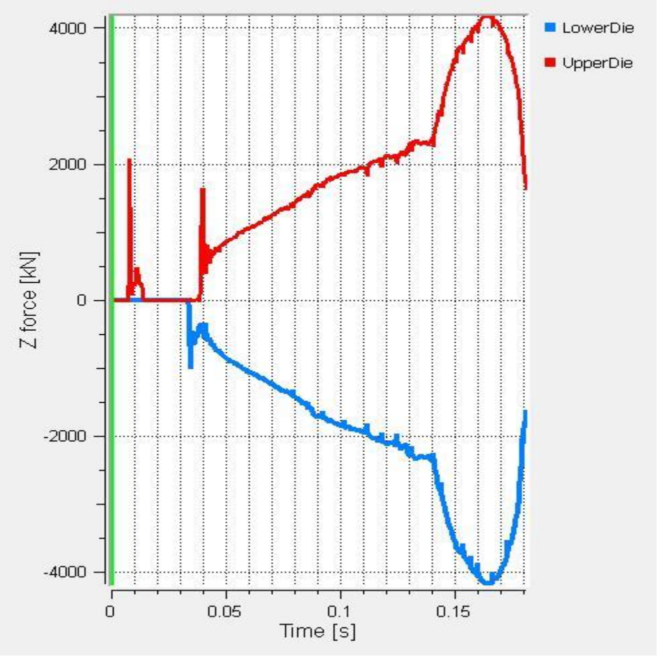

Fig.28: Die Force Variation in Both Dies (Case 4)

3D model of billet considered in case 4 is shown in Fig.25. Whereas, transparent views of billet are shown in Fig.26 and Fig.27. After simulation it has been found that maximum plastic strain act on billet is 2.16. Maximum effective stress is 182.11 MPa. Maximum Die wear in Upper Die has been found as 2.15E-11 mm. Maximum Die wear in Lower Die has been found as 7.34E-12 mm. Maximum Temperature on final forged is 1397.13°C. Maximum Strain rate in final forged part is 9.19 1/s. Average of Maximum force experienced by both dies has been found as 4172.5 kN and for this preform, Die Force variation in both dies is shown in Fig.28. It can be observed that material enter in the die cavity and creates too much flash at the outside of die cavity due to this gear has not formed with desired shape and dimensions. The Die Force and Die wear in both Dies are higher compared to all other preforms which ultimately reduces die life. Hence this perform is not suitable for net shape forging.

**CASE: 5 – Horizontal Rectangular Shape Preform**

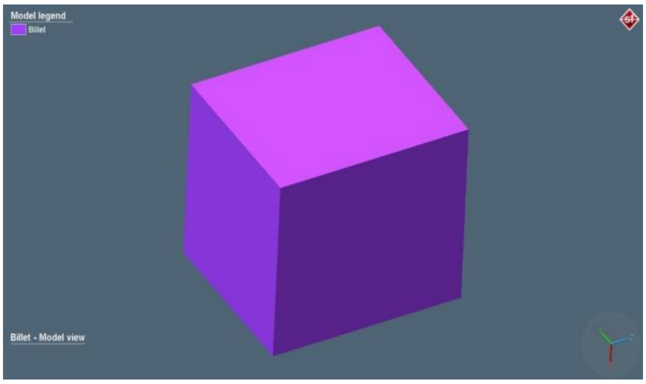

Fig. 29 – Horizontal Rectangular Shape Preform

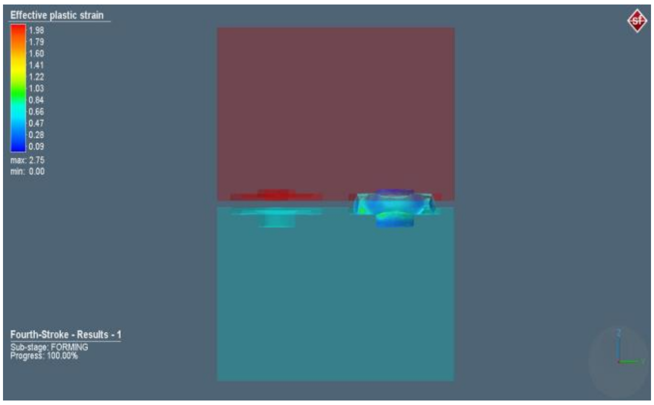

Fig.30: Transparent view after simulation (Case 5)

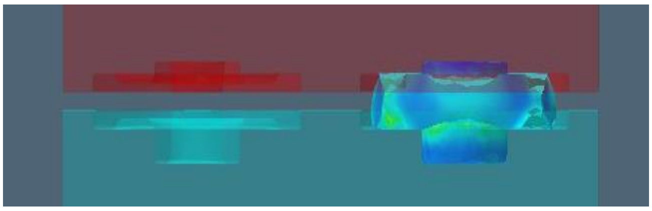

Fig.31: Magnified Transparent view after simulation (Case 5)

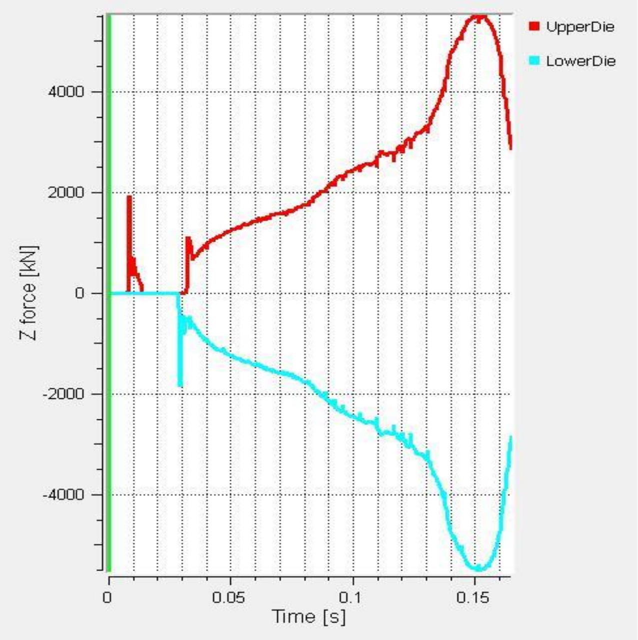

Fig.32: Die Force Variation in Both Dies (Case 5)

3D model of billet considered in case 5 is shown in Fig.29. Whereas, transparent views of billet are shown in Fig.30 and Fig.31. After simulation it has been found that maximum plastic strain act on billet is 1.98. Maximum effective stress is 166.93 MPa. Maximum Die wear in Upper Die has been found as 2.94E-11 mm. Maximum Die wear in Lower Die has been found as 9.67E-12 mm. Maximum Temperature on final forged is 1280.70°C. Maximum Strain rate in final forged part is 8.42 1/s. Average of Maximum force experienced by both dies has been found as 5504 kN and for this preform, load stroke plot is shown in Fig.32. It can be

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observed that material does not enter in the die cavity completely due to this gear has not formed with desired shape and dimensions. The material has tried to enter in the die cavity and some improved result has been found than previous one. Hence this perform is not suitable for net shape forging.

### CASE:6 – Vertical Rectangular Shape Preform

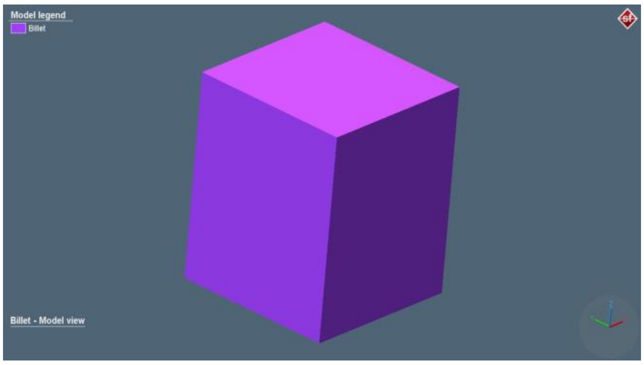

Fig. 33 – Vertical Rectangular Shape Preform

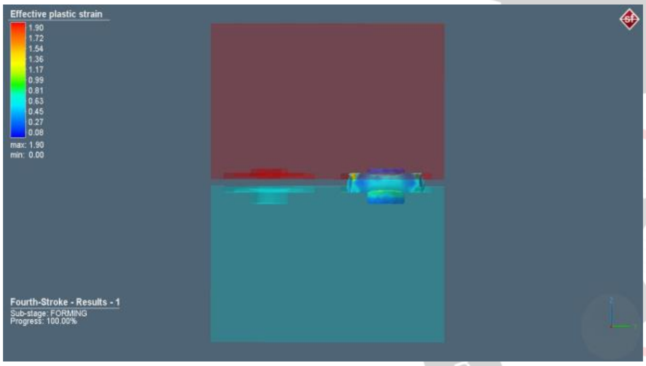

Fig.34: Transparent view after simulation (Case 6)

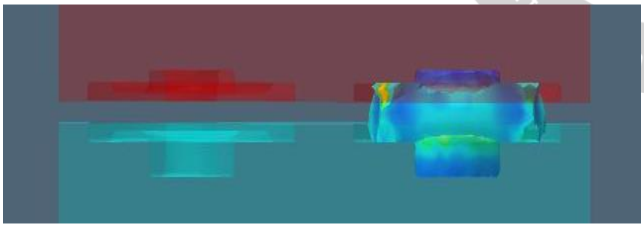

Fig.35: Magnified Transparent view after simulation (Case 6)

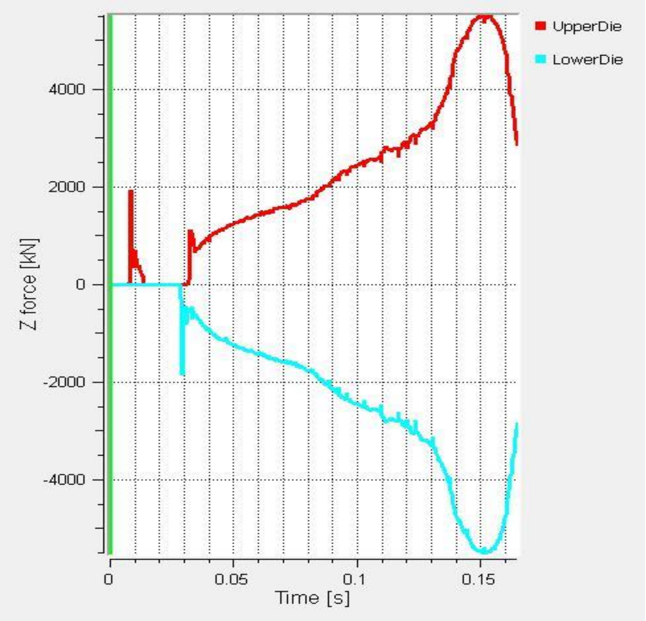

Fig.36: Die Force Variation in Both Dies (Case 6)

3D model of billet considered in case 6 is shown in Fig.33. Whereas, transparent views of billet are shown in Fig.34 and Fig.35. After simulation it has been found that maximum plastic strain act on billet is 1.90. Maximum effective stress is 160.19 MPa. Maximum Die wear in Upper Die has been found as 2.67E-11 mm. Maximum Die wear in Lower Die has been found as 9.12E-12 mm. Maximum Temperature on final forged is 1228.96°C. Maximum Strain rate in final forged part is 8.08 1/s. Average of Maximum force experienced by both dies has been found as 5176 kN and for this preform, load stroke plot is shown in Fig.36. It can be observed that material does not enter in the die cavity completely due to this gear has not formed with desired shape and dimensions. The material has tried to enter in the die cavity and some improved result has been found than previous one. Hence this perform is not suitable for net shape forging.

### CASE: 7 – Square Shape Preform

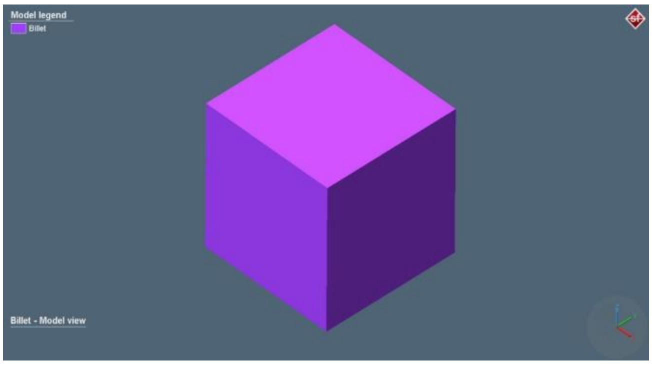

Fig. 37 – Square Shape Preform

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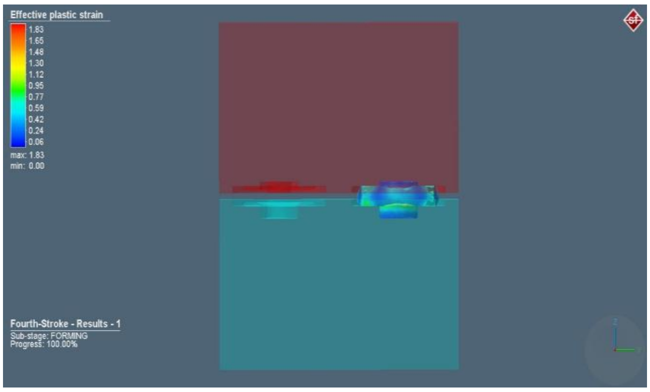

Fig.38: Transparent view after simulation (Case 7)

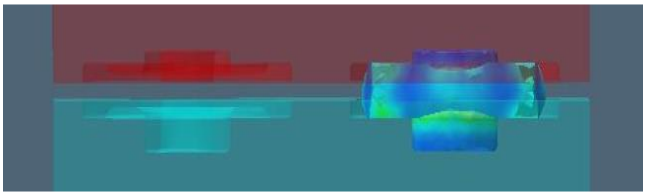

Fig.39: Magnified Transparent view after simulation (Case 7)

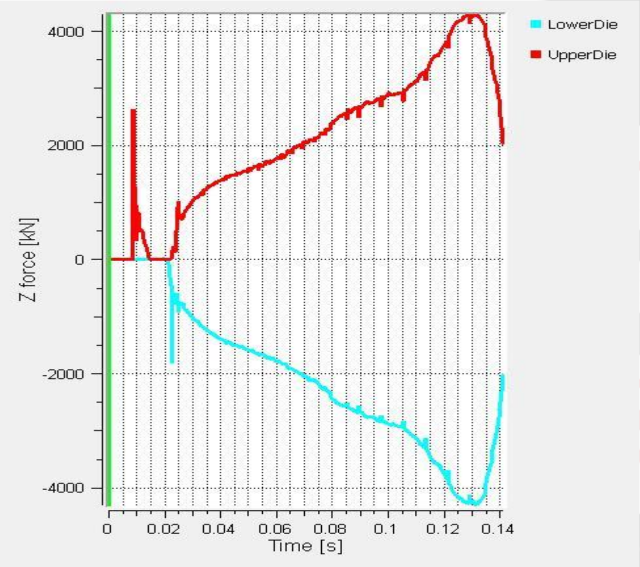

Fig.40: Die Force Variation in Both Dies (Case 7)

3D model of billet considered in case 7 is shown in Fig.37. Whereas, transparent views of billet are shown in Fig.38 and Fig.39. After simulation it has been found that maximum plastic strain act on billet is 1.83. Maximum effective stress is 154.28 MPa. Maximum Die wear in Upper Die has been found as 2.21E-11 mm. Maximum Die wear in Lower Die has been found as 7.59E-12 mm. Maximum Temperature on final forged is 1183.68°C. Maximum Strain rate in final forged part is 7.78 1/s. Average of Maximum force experienced by both dies has been found as 4304 kN and for this preform, load stroke plot is shown in Fig.40. It can be observed that material does not enter in the die cavity completely due to this gear has not formed with desired shape and dimensions. The material has tried to enter in the die cavity and some improved result has been found. Hence this perform is not suitable for net shape forging.

### CASE: 8 – Cylindrical Shape Preform

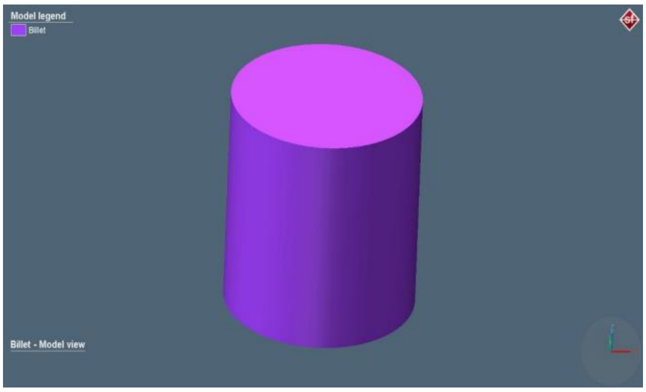

Fig.41 – Cylindrical Shape Preform

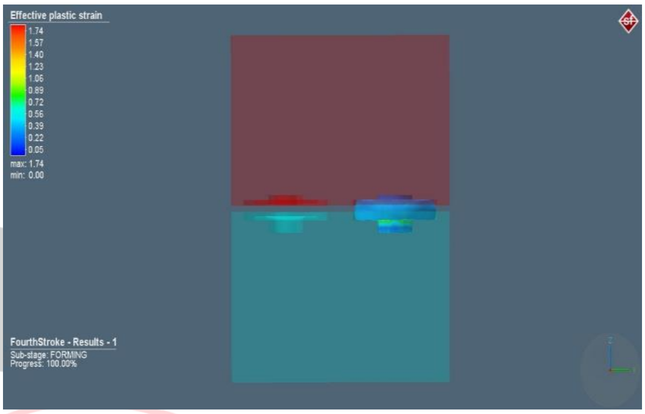

Fig.42: Transparent view after simulation (Case 8)

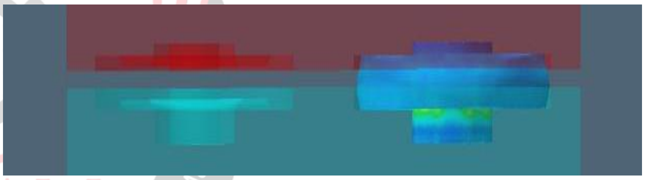

Fig.43: Magnified Transparent view after simulation (Case 8)

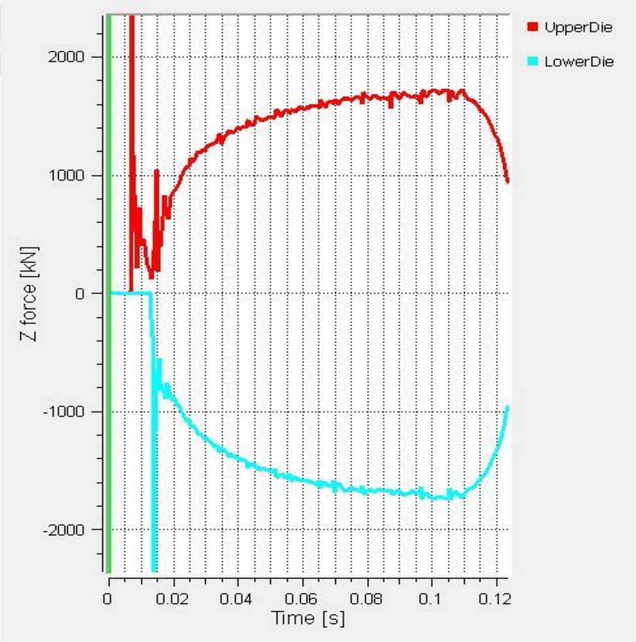

Fig.44: Die Force Variation in Both Dies (Case 8)

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3D model of billet considered in case 8 is shown in Fig.41. Whereas, transparent views of billet are shown in Fig.42 and Fig.43. After simulation it has been found that maximum plastic strain act on billet is 1.74. Maximum effective stress is 146.70 MPa. Maximum Die wear in Upper Die has been found as 1.21E-11 mm. Maximum Die wear in Lower Die has been found as 4.16E-12 mm. Maximum Temperature on final forged is 1125.47°C. Maximum Strain rate in final forged part is 7.40 1/s. Average of Maximum force experienced by both dies has been found as 2354.5 kN and for this preform, load stroke plot is shown in Fig.44. It can be observed that material enter in the die cavity uniformly due to this gear has formed with desired shape and dimensions by allowing equal amount of space at outside edge for safely removal of final forged part from cavity. Hence this perform is suitable for net shape forging.

## VI. COMPARISON OF RESULTS:

Various parameters such as Effective Plastic Strain, Effective Plastic Stress, Temperature, Maximum Strain rate, die wear in both dies, die force experienced by both dies is compared for all eight preform shapes.

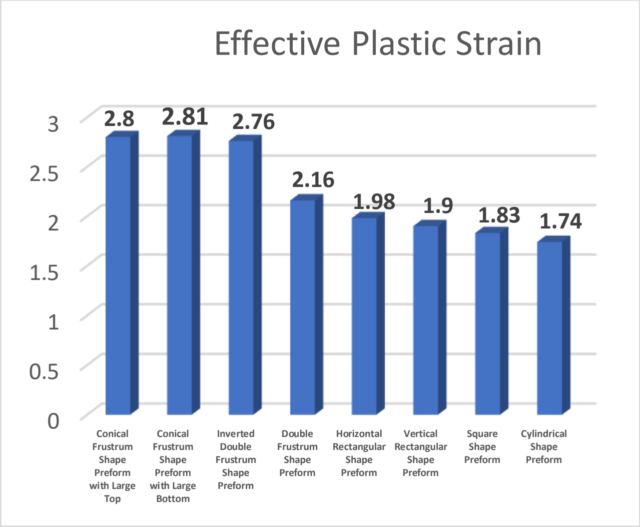

Fig.45 – Comparison of Effective Plastic Strain in all eight Preform Shapes

It can be observed that maximum Effective Plastic Strain is maximum in case 2 and minimum in case 8. It can be seen in Fig.45. Lower effective strain in forging billets has several advantages, such as improved mechanical properties like strength and toughness, enhanced microstructure, which leads to improved material performance, reduced cracking risk, improved process reliability, improved dimensional accuracy, and enhanced surface quality. This is one of the reasons why cylindrical shape preform is better.

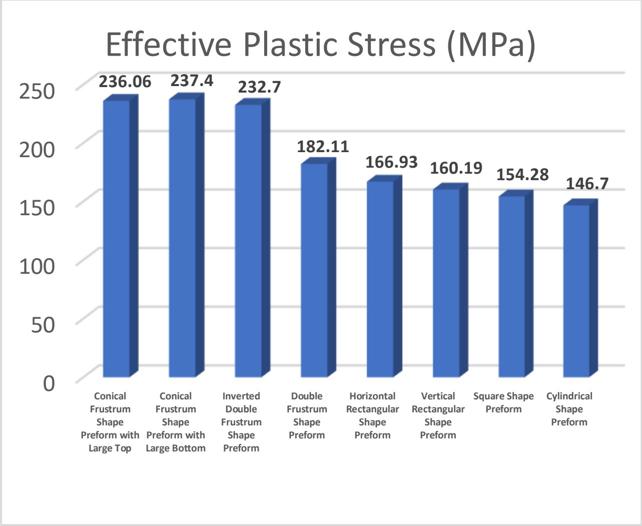

Fig.46 – Comparison of Effective Plastic Stress in all eight Preform Shapes

It can be observed that maximum Effective Plastic Stress is maximum in case 2 and minimum in case 8. It can be seen in Fig.46. It indicating Conical Frustrum Shape Preform with Large Bottom has less toughness than all other preform shapes because its effective stress is highest. On the other hand, Cylindrical Shape Preform has the highest toughness compared to all other preform shapes because its effective stress is lowest.

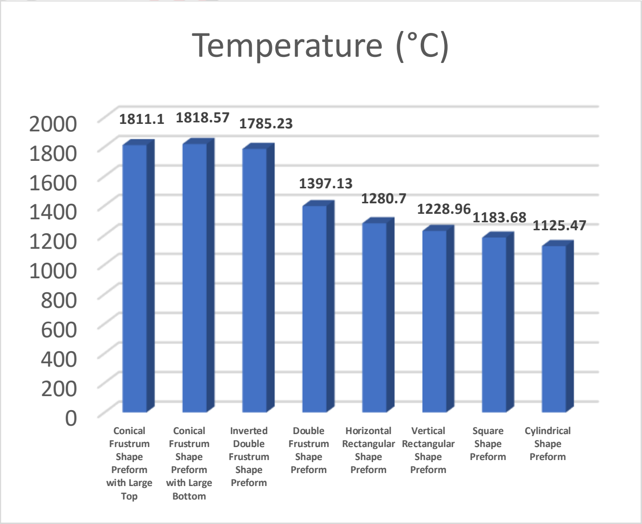

Fig.47 – Comparison of Temperature distribution in all eight Preform Shapes

It can be observed that temperature is maximum in case 2 and temperature is minimum in case 8. It can be seen in Fig.47.

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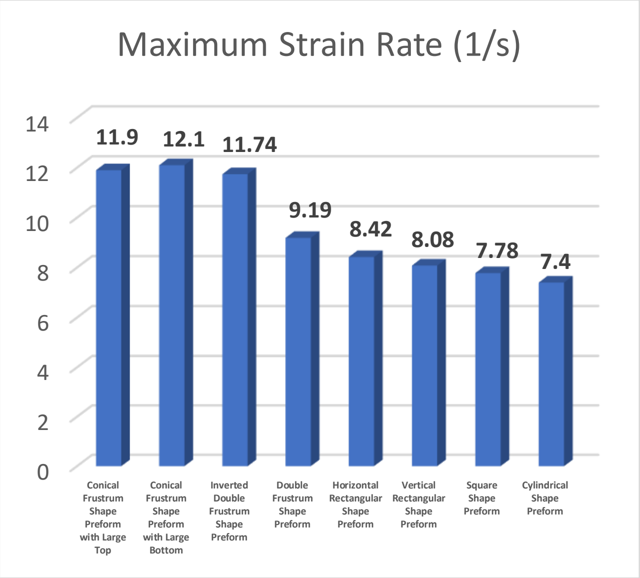

Fig.48 – Comparison of Maximum Strain Rate in all eight Preform Shapes

It can be observed that maximum strain rate is highest in case 2 and maximum strain rate is minimum in case 8. It can be seen in Fig.48. Strain rate is less in Cylindrical Shape Preform compared to all other preforms which describe that Cylindrical Shape Preform is having more toughness and machinability as compared to all other preform shapes. Since Constant Mesh Gear is used in the Low-Speed Gear Application, it required the material which is having more toughness. Therefore, Cylindrical Shape Preform is more suitable than all other preform for Constant Mesh Gear Application.

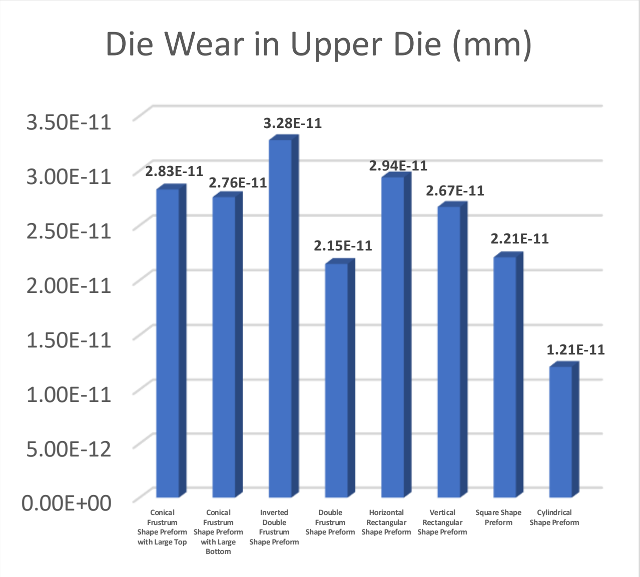

Fig.49 – Comparison of Die Wear in Upper Die in all eight Preform Shapes

It can be observed that Die wear in Upper Die is maximum in case 3 and it is minimum in case 8. It can be seen in Fig.49. Die wear in Upper Die is less while using Cylindrical Shape Preform compared with other preform shapes which describes that use of Cylindrical Shape Preform ultimately increases the die life.

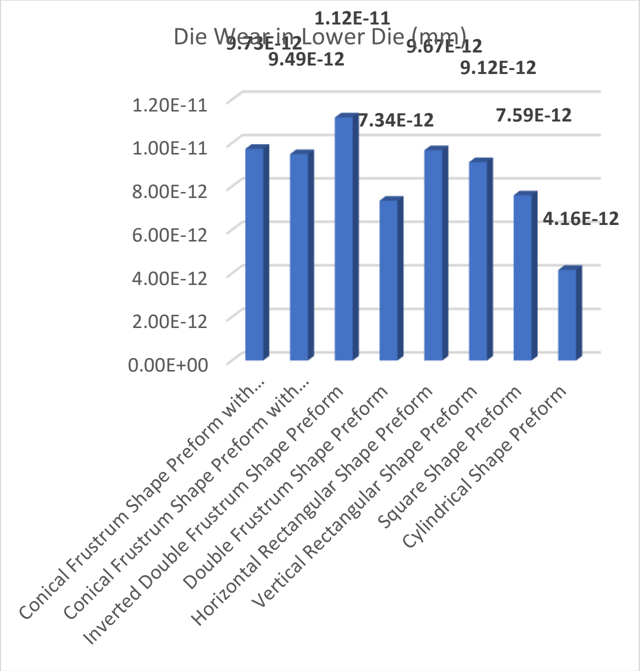

Fig.50 – Comparison of Die Wear in Lower Die in all eight Preform Shapes

It can be observed that Die wear in Lower Die is maximum in case 2 and it is minimum in case 8. It can be seen in Fig.50. Similar to Upper Die, die wear in Lower Die is less while using Cylindrical Shape Preform compared with other preform shapes which describes that use of Cylindrical Shape Preform ultimately increases the die life.

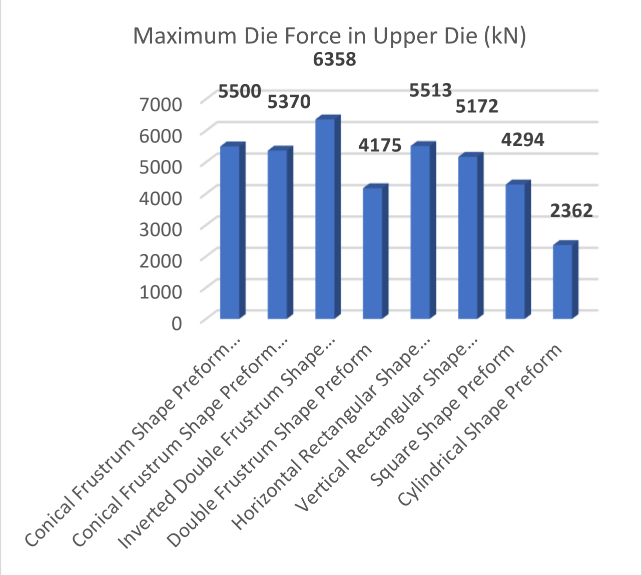

Fig.51 – Comparison of Maximum Die Force in Upper Die for all eight Preform Shapes

It can be observed that maximum die force in upper die is highest in case 3 and it is lowest in case 8. It can be seen in Fig.51. It can be said that cylindrical shape preform is more forgeable other preform shapes as the maximum die force in upper die in case of the cylindrical shape preform is less compared to that of all other preform shapes.

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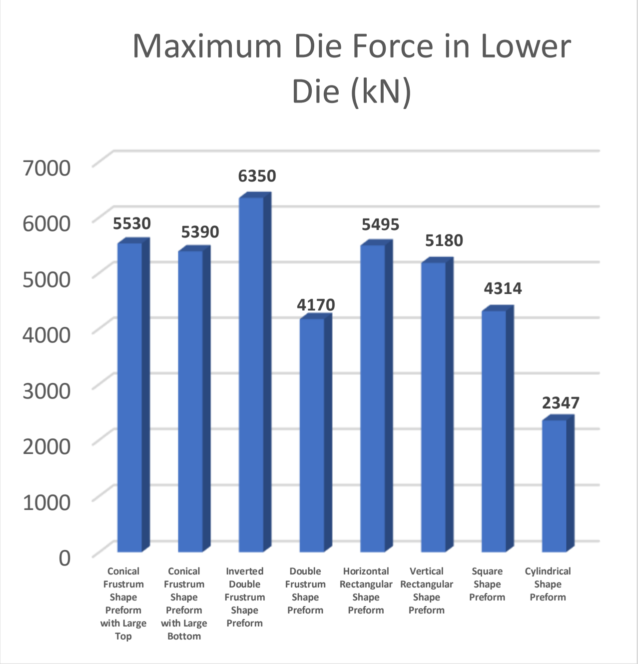

Fig.52 – Comparison of Maximum Die Force in Lower Die for all eight Preform Shapes

It can be observed maximum die force in lower die is highest in case 3 and it is minimum in case 8. It can be seen in Fig.52. Similar to the upper die, it can be said that cylindrical shape preform is more forgeable other preform shapes as the maximum die force in lower die in case of cylindrical shape preform is less compared to that of all other preform shapes.

## VII. CONCLUSION

Following useful information have been concluded after doing the study of all eight preform shapes:

1. Any non-symmetric preform shape prone to result in defects such as underfilling and excessive flash.
2. For manufacturing a symmetric component by forging, a reasonable volume distribution is key to optimize the preform.
3. It is observed that out of eight, only one preform which is, ‘cylindrical shape preform’, could result in near net shape forging.
4. The use of cylindrical shape preform is suggestable for the constant mesh gear since it causes less amount of die wear and die force in both dies which ultimately increases die life.
5. Through the use of simulation techniques, it is possible to determine the most efficient method of producing the components, and to ensure reduced material and labor cost.

## VIII. ACKNOWLEDGEMENT:

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## IX. CONFLICT OF INTEREST:

The authors declare that they have no conflict of interest.

## X. REFERENCES

[1] Zhou Wenjing, Sun Zhichao, Zuo Shupeng, Yang He, Fan Xiaoguang, “Shape optimization of inlet billet for TA15 Ti-Alloy Complex Components Preforming”, *Rare Metal Materials and Engineering,*2011, v.40, pp.951-956.

[2] Nagarajan Thiyagarajan, Ramana V. Grandhi, “Multi-level design process for 3-D preform shape optimization in metal forming”, *Journal of Materials Processing Technology,*2005, v.140, pp.421-429.

[3] Jae-Jun Lee, Ui-Jin Jung, Gyung-Jin Park, “Shape optimization of the workpiece in the forging process using equivalent static loads”, *Finite Elements in Analysis and Design,*2013, v.69, pp.1-18.

[4] Sunil Mangshetty, Santosh Balgar, “Billet shape optimization for minimum forging load using FEM analysis”, *International Journal of Engineering Research and Development,*2012, v.3, pp.11-16.

[5] Akkaram Srikanth, Nicholas Zabaras, “Shape optimization and preform design in metal forming Processes”, *Computer Methods Applied Mechanics and Engineering,*2000, v.190, pp.1859-1901.

[6] M.Haider, K.K.Pathak, Geeta Agnihotri, “Preform design for near net shape close die gear forging using simulation technique”, *Archives of Applied Science Research,*2010, v.2(6), pp.317-324.

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