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Simulation of Closed die forging for Stud Bolt and Castle Nut using AFDEX

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Abstract*— The purpose of this paper is to simulate the closed die forging process, prediction of defect and eliminating it to increase the product life. The task is to simulate the stud bolt and castle nut using AFDEX software. Three types of die sets for stud bolt and one type of die set for castle nut are analyzed to find the optimum die set for facilitating filling of the die completely by the material enabling lower stresses.

Index Terms— **AFDEX, Closed die forging, Die sets, Stresses.**

I. INTRODUCTION

Forging is defined as the process in which a metal billet or blank is shaped by tools or dies with application of temperature and pressure [1]. There is a renewed interest in analyzing forging process by different simulation techniques [2-5]. In earlier research works, a three-dimensional model using MSC/DYNA is used to simulate a closed die forging process [6]. An H-shaped cross-section forging die and a rectangular billet are modeled. Die/billet interface contact friction, and die geometry are varied to determine the effects of these variables on material flow, stress, strain, and die force. An attempt has been made to compute the load requirement in the closed die forging process by using MSC Super Forge during different stages of the process [7]. Lower production costs aided by higher volumes allowed an intensive use of forging. Manufacturing companies have especially focused on producing a complex shaped part with a tight dimensional tolerance. Traditional hot and cold forging methods have their own limitations to produce such a complex shaped part, hot forging requires complex system with relatively higher manufacturing cost, while cold forging is not applicable to materials with limited formability. Thereby, multistage forging is advantageous to produce complex shaped parts. In order to build a multistage forging system, it is necessary to characterize mechanical properties in response to system design parameters, such as temperature, forging speed [8]. In the recent paper [9] different die configurations and billet shapes are experimented in order to produce the best configuration and subsequently supported by forging simulation package called Super Forge for process optimization and they got to know that Super Forge simulations seem to give the desired results. Closed die forging is a very complex process and the measurement of actual forces for real material is difficult and cumbersome. Hence the computer simulation modeling technique has been adopted to get the estimated load requirement. The objective of this research work is to simulate and analyze the closed die forging process [10]. Production of automobile stud bolt and castle nut through forging simulation process is affected by many parameters such as billet temperature, geometry of die and geometry of pre-formatted billet. Three-dimensional modeling of component and the corresponding dies are performed by CATIA software, while simulation and analysis of forging are performed by AFDEX (Advisor as friend for Forging Design Experts) software, having the capability of checking the die filling, defect formation. The prominently used simulation software in the forging industry 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, final shape etc.,. It is observed that the software can be effectively used to optimize the forging simulation process to maximize the mechanical strength, minimize material scrap or improve yield and forging stages and hence reduce the overall cost of manufacture.

II. METHODOLOGY

A. *Simulation Procedure*

For the present analysis, the steps are enlisting in Figure 1. Initially we considered a part or component for the analysis and then developed the CAD model of the component using Catia software. Corresponding to the CAD model, we designed suitable dies. With respect to the process, material composition and properties given for the product, select the suitable die material. Finally forging simulation is carried out by using the forging simulation software called AFDEX (Advisor as friend for Forging Design Experts). If any defects are present, changes are made in the dies. This leads to improved results in the final product. This forging simulation process will continue till we get product with least defects.

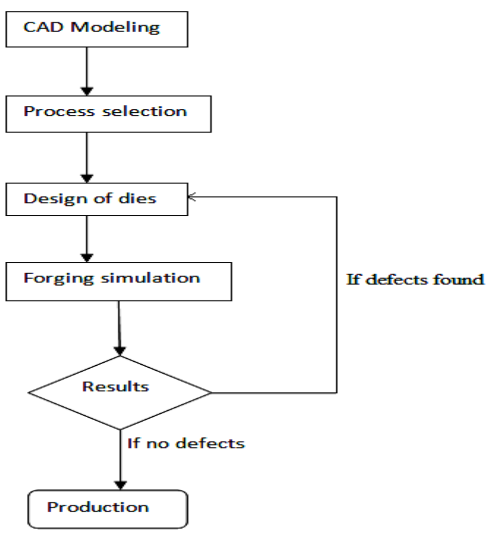

Fig.1. Simulation steps

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After the simulation got over with least defects, then the product goes for production. Figure 2 shows part drawing of the stud bolt and Castle nut considered for the analysis. The work piece material considered for the present analysis is EN (Euro Norms) 24 alloy steel. The chemical composition, Mechanical and physical properties of EN 24 alloy steel are presented in Table I and Table II.

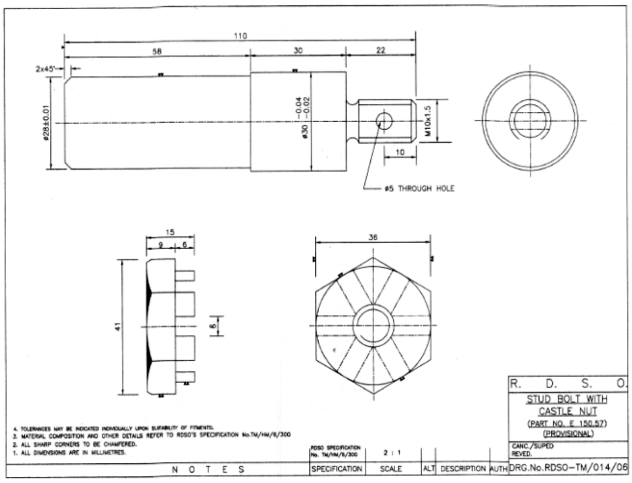

Fig.2. Part drawing of stud bolt and castle nut

TABLE I. Chemical Composition of EN24 alloy steel in %

Carbon	0.38-0.43
Silicon	0.10-0.35
Manganese	0.60-0.80
Nickel	1.65-2
Chromium	0.70-0.90
Molybdenum	0.20-0.30
Sulphur	0.050 (max)
Phosphorous	0.050(max)

TABLE II. Properties of EN 24 alloy steel

Tensile strength	758 MPa (77 kgf/mm²)
Yield strength	606 MPa (62 kgf/mm²)
Hardness Rockwell C	17
Density	7850 kg/m³
Poisson's ratio	0.29
Forging temperature	871°C – 1204°C

B. Modeling in CATIA software

3D modeling software CATIA is used to model the part, billet, and dies. Modeled components are shown in Figure 3 and Figure 4.

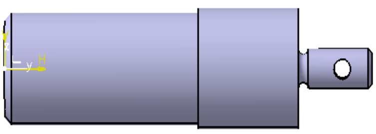

Fig.3. 3D model of stud bolt

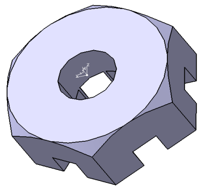

Fig.4. 3D model of castle nut

For simulation purpose, machining allowance of 0.5 should be added for all sides of the component. But in manufacturing, machining allowance should be added depending on physical structure of the component. In stud bolt and castle nut intricate portions are pocket creation, groove cutting and thread cutting operations. Forging cannot be done in those intricate portions. Figure 5 and Figure 6 shows stud bolt and castle nut after neglecting intricate portions to facilitate smooth forging.

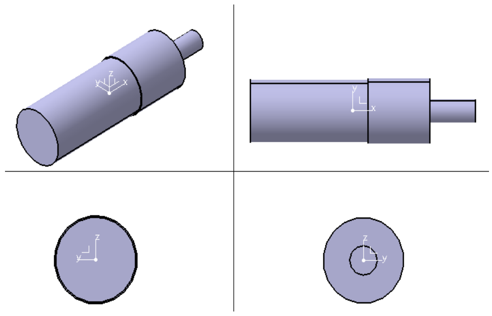

Fig.5. Modeled component of the stud bolt after neglecting intricate portions and adding 0.5 mm machining allowance for all sides of the component

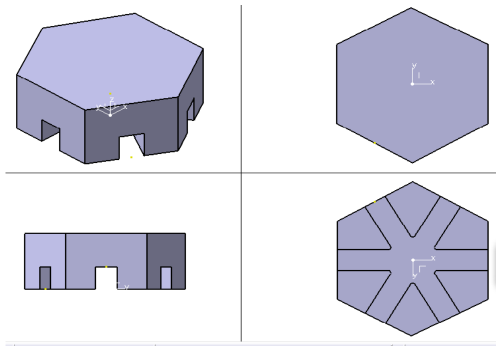

Fig.6. Modeled component of the castle nut after neglecting intricate portions and adding 0.5 mm machining allowance for all sides of the component

CATIA provides option of Boolean operation by which specific shape can be subtracted or added to the other shape. If the part is simple, Boolean operation can be used to design the upper die and lower die. Even though AFDEX allows dies and billets to move in X, Y and Z directions and rotate about X, Y and Z directions it causes lot of problems in positioning, if they are aligned manually. So care must be taken while modeling dies and billet in CATIA.

As the given part has circular cross-section along Y axis, a cylindrical billet is used. Dies and billets are drawn in such a manner that they are all aligned in the same axis. As AFDEX accepts only '.STL' files, upper die, lower die and billet are saved with '.STL' extension. All the files of dies and billets

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with '.STL' extension are imported to AFDEX database. Appropriate forging parameters used for the simulation are enlisted in Table III, and these parameters are provided to the AFDEX database.

TABLE III. Forging Parameters

Type of Forging	Hot Close-Die- Forging (HCDF)
Work Piece Material	EN 24 alloy steel / AISI 4340
Die Material	HCHCr D2 tool steel
Press Type	Crank press
Friction Type	Coulomb Friction
Coefficient of Friction	0.3
Draft angle for die for ease of ejection	5-7 degree

C. Analysis in AFDEX for stud bolt

Billet volume for stud bolt is determined as,

Billet volume required= Volume of the component + 6% extra (for complete die fill) from volume of the component [11].Volume of the stud bolt = 6.157 E^{-5} m^3 Therefore, billet volume required for stud bolt = 6.157 E^{-5} m^3 + 3.69 E^{-6} m^3 ≈ 6.52 E^{-5} m^3.The upper and lower dies are shown in Figure 7 and 8 for FIRST iteration.

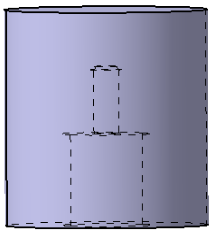

Fig.7. Upper die for iteration 1

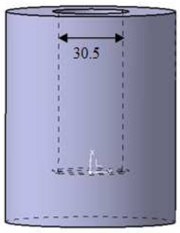

Fig.8. Lower die for iteration 1

Minimum load required for deforming the material = Yield strength of the work piece material used x Area of the component. That is, projected area of forging or Area of forging at parting plane [12].

Area of forging at parting plane= πr^2

$= \pi (15.25)^2$ (Figure 8)

$= 730.61\ mm^2$

Therefore, Load required = 606 MPa (N/mm^2) x 730.61 mm^2

= 442749.66 N (442.749.66 KN)

≈ 50 ton

Minimum of 50 tons load is required to deform the material. By using the parameters and calculations simulation is carried. Figure 9 shows the initial billet is going to forge between upper and lower dies. Figure 10 shows that the die cavity is not completely filled and the stress at some points is greater than ultimate stress corresponding to the work material used. In the Figure10, the maximum stress found is 163 kgf/mm^2 which is greater than ultimate strength of the material that is, 77 kgf/mm^2. Results are shown in Table IV.

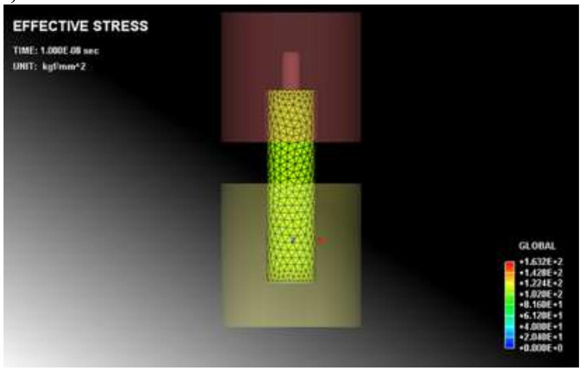

Fig.9. Initial billet going to forge between Upper and lower dies

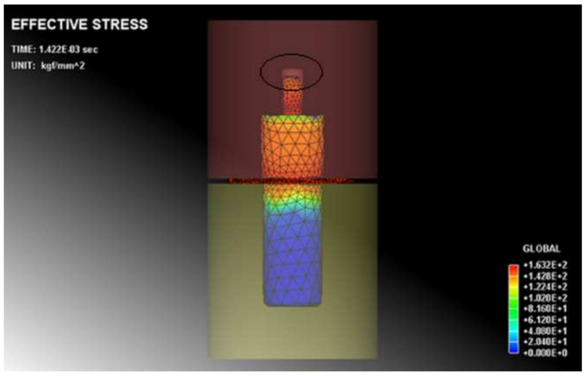

Fig.10. Die cavities are not completely filled

TABLE IV. Result table of iteration 1 for stud bolt

Global values Of stress (kgf/mm^2) obtained in simulation at the end of the stroke	Ultimate stress of the work material used (kgf/mm^2)	Observation
+1.632 $E+^2$ (163.2) >	77	Component fails during production
+1.428 $E+^2$ (142.8) >	77	
+1.224 $E+^2$ (122.4) >	77	
+1.021 $E+^2$ (102.1) >	77	
+8.160 $E+^1$ (81.60) >	77	
+6.120 $E+^1$ (61.20) <	77	Feasible solution
+4.080 $E+^1$ (40.80) <	77	
+2.040 $E+^1$ (20.40) <	77	
+0 $E+^\circ$ (0) <	77	

The simulation result shows, metal does not completely fill the die cavity and the stresses are exceeding at some points of the component shown in fig. 10. The reason might be the geometry of the preformed billet and smaller flash area. Table IV shows the stress values obtained in the simulation. At some points of the work piece stresses are exceeding and thereby component will fails during production at points where the stresses are more. So we carried simulation again as iteration 2 by changing the billet height and diameter ratio with constant volume and also changed the die design for enabling lower stresses. The upper and lower dies are shown in Figures 11 and 12 for iteration 2. Again we carried out the simulation by changing die design for facilitating filling of the die completely by the material enabling lower stresses.

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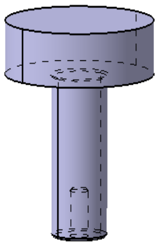

Fig.11. Upper die for iteration 2

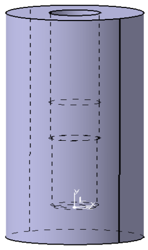

Fig.12. Lower die for iteration 2

The minimum load required to deform the material is same as in iteration 1, because projected area is same. Figure 13 shows the initial billet is going to forge between upper and lower dies. Figure 14 shows that the die cavity is completely filled but still at some points stresses are greater. In Figure 14 the maximum stress found is 165 kgf/mm² which is greater than ultimate strength of the material that is, 77 kgf/mm². Results are presented in Table V.

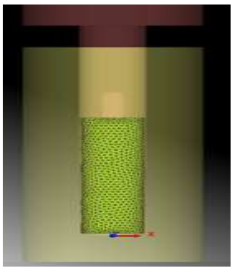

Fig.13. Initial billet going to forge between upper and lower dies

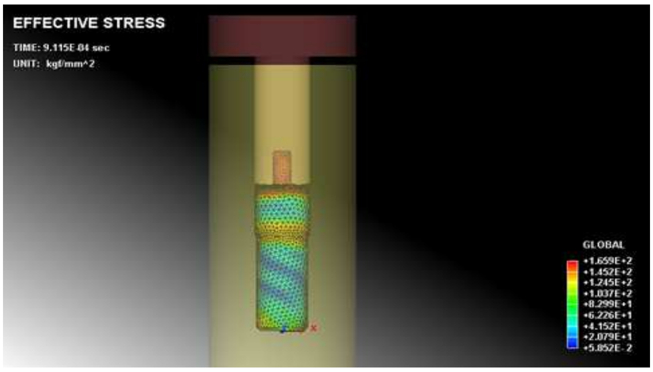

Fig.14. Die cavities are completely filled

TABLE V. Result table of iteration 2 for stud bolt

Global values Of stress (kgf/mm²) obtained in simulation at the end of the stroke	Ultimate stress of the work material used (kgf/mm²)	Observation
+1.659 E+² (165.9) >	77	Component fails during production
+1.452 E+² (145.2) >	77	
+1.245 E+² (124.5) >	77	
+1.037 E+² (103.7) >	77	
+8.299 E+¹ (82.99) >	77	
+6.226 E+¹ (62.26) <	77	Feasible solution
+4.152 E+¹ (41.52) <	77	
+2.079 E+¹ (20.79) <	77	
+5.852 E-² (0.058) <	77	

In this simulation, the metal is completely filled the die cavity but the stresses are exceeding the ultimate stress at some points of the component shown in fig 14. Hence we observed that, reverse flow of metal and smaller flash area are affecting the enabling of lower stresses. Table V shows the stress values obtained in the simulation. At some points of the component, stresses are exceeding and thereby component fails during production at points where the stresses are more.

By keeping these parameters in mind by providing larger flash area and avoiding reverse flow of metal, we modelled the dies for next iteration. So we carried simulation again as iteration 3 by changing the die design for enabling lower stresses. We modelled the upper and lower dies for iteration 3 by providing larger flash area and avoiding reverse flow of metal. Now dies are axis symmetric as shown in Figure 15 and 16.

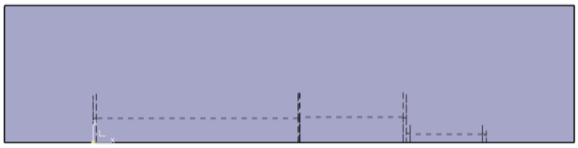

Fig.15. Upper die

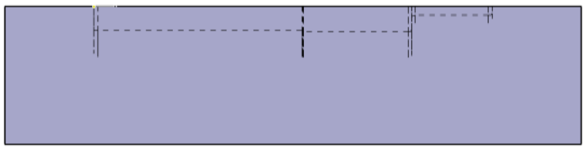

Fig.16. Lower die

Minimum load required for deformation or minimum capacity required for the press to deform the material for Figure 17 is formulated as:

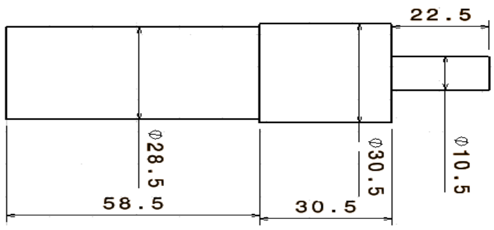

Fig.17. Projected area in iteration 3

Projected area = Width X Height

= (58.5 x 28.5) + (30.5 x 30.5) + (22.5 x 10.5)

= 2833.75 mm²

Therefore, Load required = 606 MPa (N/mm²) x 2833.75 mm²

= 1717252.5 N (1717.25 KN)

≈ 193 ton

Minimum of 193 tons load is required to deform the material. Figure18 shows the initial billet is going to forge between upper and lower dies and Figure 19 shows that the die cavity is completely filled.

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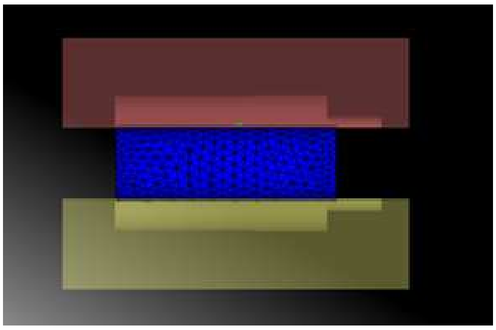

Fig.18. Initial billet is going to forge between upper and lower dies

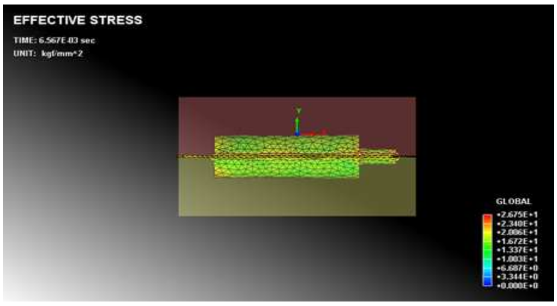

Fig.19. Die cavities are completely filled

The final part represented in Figure 19 is feasible as stresses obtained are less than the ultimate stress of the work piece material and the product goes for production. Also we observed from the Table VI stresses are not exceeding the ultimate stress.

TABLE VI. Result table of iteration 3 for stud bolt

Global values of stress (kgf/mm²) obtained in simulation at the end of the stroke	Ultimate stress of the work material used (kgf/mm²)	Observation
+2.675 E+¹ (26.75) <	77	
+2.340 E+¹ (23.40) <	77	
+2.006E+¹ (20.06) <	77	
+1.672 E+¹ (16.72) <	77	Feasible solution
+1.337 E+¹ (13.37) <	77	
+1.003 E+¹ (10.03) <	77	
+6.687 E+° (6.687) <	77	
+3.344 E+° (3.344) <	77	
+0.000 E+° (1) <	77	

Figure 20 presents plot of load as a function of stroke. In Figure 20, Dies contact the work piece at a point A and is approximately for 0.004 s, then the flash begins to form at B for 0.005 s at a load approximately equal to 50 tons, thereafter load increases sharply at point C and the pressure should be sufficient to fill the entire die cavity. However, for ensuring proper dimensions of forging an extra load may be required as indicated by point D. The maximum load the press utilized to forge completely is 429 tons shown for approximately for 0.0065 s. Hence this component can be forged completely by using a press, having a minimum capacity of 429 tons or greater.

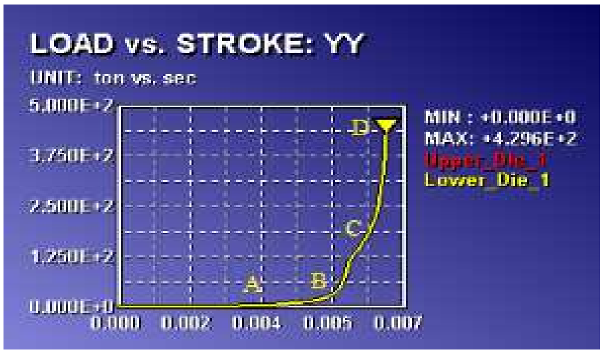

Fig.20. Maximum load the press utilized to deform the material is 429 tons

D. Analysis in AFDEX for castle nut

Billet volume for castle nut is determined as,

Billet volume required= Volume of the component + 6% extra from volume of the component
Volume of the castle nut = 1.463 E^{-5} m³
Billet volume required for Castle nut= 1.463 E^{-5} m³ + 8.778 E^{-7} m³ ≈ 1.55 E^{-5} m³

Dies for castle nut by providing larger flash area for enabling the lower stresses are represented in the Figures 21 and 22.

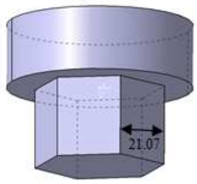

Fig.21. Upper die

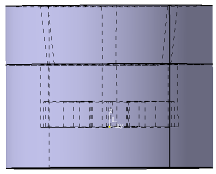

Fig.22. Lower die

Minimum load required for deforming the material= Yield strength of the work piece material used x Area of the component.
Area of hexagon or projected area = (Length) ² X 2.6
= (21.07)² X 2.6
= 1154.58 mm²
Therefore, Load required = 606 MPa (N/mm²) x 1154.58 mm²
= 699678.786 N (699.678 KN)
≈ 79 ton
Minimum of 79 tons load is required to deform the material. Figure 23 shows the initial billet is going to forge between upper and lower dies and figure 24 shows that the die cavity is completely filled. The final part represented in figure 24 is feasible as stresses obtained are less than the ultimate stress of the work piece material and the product goes for production. Results are shown in table VII.

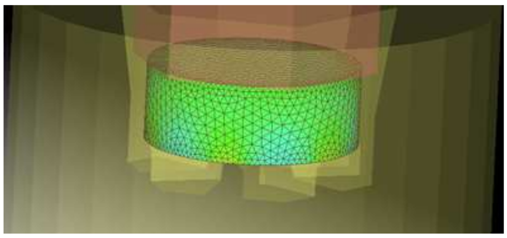

Fig.23. Initial billet going to forge between upper and lower dies

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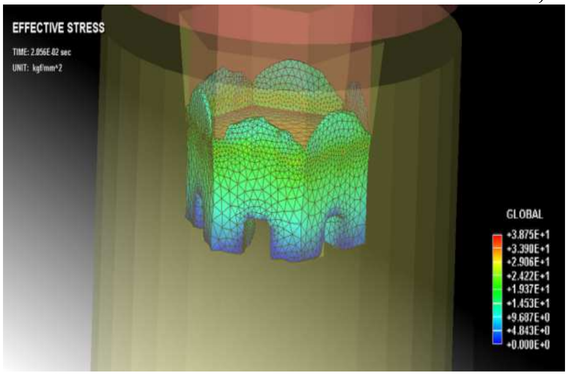

Fig.24. Die cavities are completely filled

Table VII. Result table for castle nut

Global values of stress (kgf/mm²) obtained in simulation at the end of the stroke	Ultimate stress of the work material used (kgf/mm²)	Observation
+3.875 E^{+1} (38.75) <	77	Feasible solution
+3.390 E^{+1} (33.90) <	77	
+2.906 E^{+1} (29.06) <	77	
+2.422 E^{+1} (24.22) <	77	
+1.937 E^{+1} (19.37) <	77	
+1.453 E^{+1} (14.53) <	77	
+9.687 E^{+0} (9.687) <	77	
+4.843 E^{+0} (4.843) <	77	
+0.000 E^{+0} (1) <	77	

We observed from the table VII, all the stress values in the final part is less than ultimate stress of the material used. This is feasible solution and the component goes for production. In Figure 25, Upper and lower dies are comes in contact the work piece at a point A and is approximately at the origin itself, then the flash begins to form at B approximately for 0.005 s at a load nearly equal to 75 tons, thereafter load increases sharply towards point C and that pressure should be sufficient to fill the entire die cavity. However, for ensuring proper dimensions of forging an extra load may be required as indicated by point D is 275 tons. The forging simulation completes approximately for 0.0015 s. Hence castle nut can be forged completely by using a press, having a minimum capacity of 275 tons or greater.

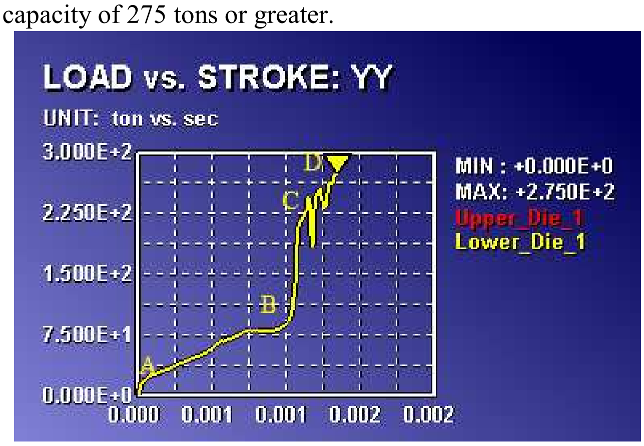

Fig.25. Maximum load the press utilized to deform is 275 tons

III. CONCLUSION

From the above discussion it can be concluded that

- This paper presents a method for performing 3-D forging simulations through AFDEX.
- Three types of die sets for stud bolt and one type of die set for castle nut have been tried and forging simulation process can be analyzed. Optimum die set for which die cavity fills completely while maintaining a lower stress is presented. These efforts allow the engineer to identify the process deficiencies easily before the actual production starts, leading to cost and time saving.
- The unfilling defect obtained in stud bolt has been eliminated.
- AFDEX software is found to be very helpful in simulating and analysing forging simulation process.
- The stresses present in the final component is less than ultimate stress of the work material used, thus increases the product life.

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