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# FE Optimization Studies on AA7075 Pre-Form Geometry of AUV Propeller Front and Back Hub for Zero under-Fill and Low Flash Cold Forging

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***Abstract*: The complex three-dimensional geometry and tooling design of precision propeller components by forging technology is impeded by numerous barriers to date. Cold forging, an incremental metal forming process, has great potential to improve the current situation owing to its flexibility and lower tool load requirement. Manufacture of autonomous under water (AUV) propeller owing to complex hubs and blade design poses challenges to researchers who aim to increase thrust. The proposed work investigates cold forging process adopted to produce propeller hubs that involve flash and under-fill as impending problems that can be efficiently solved by proper design and optimization of pre-form. The 3D rigid-plastic finite element (FE) model of cold forging of AA7075 alloy propeller front and back hub was developed under SOLIDWORKS and AFDEX-3D 2014SP0 platform. Four FE modeling approaches have been proposed and simulated by finite element and have been successful in understanding of metal flow, work optimization and die stress in forming process. The AA7075 pre-form with AISI D2 die material for front and back hub considering four pre-forms of various dimensions were investigated for minimization of flash and under-fill. The reported work exposed that pre-form geometry had an important role to play in deciding the dimensional accuracy of the cold formed hubs. The numerical simulations provided interesting results for the optimization of front and back hub geometry that can provide input for experimentation.**

***Index Terms* — Cold forging, AA7075, volumetric analysis, flash, AFDEX, under-fill .**

## I. INTRODUCTION

The AA7075 alloy has interesting mechanical properties, like, low density, high strength, moderate ductility and toughness to quality alloy for high stress structural parts [1]. This material finds applications in parts constituted in aircraft fittings, gears and shafts, missile, regulating valve, keys and various other parts of commercial aircrafts and aerospace vehicles [2]. The automotive industry in recent years has witnessed material saving and cost reduction to have gained increased importance due to rise in demand for high volume precision parts for which precision forging is considered to be suitable [3-4]. Cold forged part with excellent tolerances and surface finish due to the absence of thermal expansion and scale formation eliminate post forging machining operations [5]. Autonomous underwater vehicle (AUV) refers to robotic device driven by the propulsion system controlled through computer programme interfaced to navigation aids like inertial measurement unit, SONAR, laser rangers and pressure sensors to facilitate maneuverability [6]. The AUV propeller manufacture involves various processes by casting, machining and forging but generally manufactured by casting [7-8]. The cast propeller are poor on part strength and surface finish, and it usually require machining to obtain desired surface quality, that however become difficult for complicated profiles that are difficult and time consuming [9]. The tool-work piece collision, material wastage and tool vibration are more compared to that in the forging process [10]. Grain structure cannot be controlled through machining on account of propeller having complex profile that demand stringent manufacturing tolerance to be carried out in order to avoid component error [11].

The metal forming simulation covers parameters detailed into three groups that include geometry, process (punch motion, temperature and friction) and material (work hardening, strain rate hardening) domains of manufacturing. The process simulation includes metal flow and details of die fill, prediction of flow defects like folds/laps, distribution of strain, strain rate and stress in material and mechanical properties like friction [12]. These lead to an improvement in die and process design and hence to achieve reduction in cost and improvement in product quality [13]. The Computer Aided Engineering (CAE) in forging process design has risen remarkably to overcome difficulties in recent design environment [14]. FE simulation was proposed as an alternative to the coupled die/component modeling approach [15]. The DEFORM-2DTM V7.2 is used for the FEM analysis of both rigid and elastic materials used in die models during forging cycle with work piece defined to be rigid–plastic or elasto-plastic material [16].

 

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The forming for complex geometries like propeller hubs and blade has been reported by researchers only few. The manufacturing of propeller using Verton long glass fibre reinforced polyamide thermoplastics was reported considering injection molding [17]. The hot forging of aerofoil blades performed through smooth Bezier surfaces modeled using Abaqus / Explicit FE software has been reported [18]. Shape deposition manufacturing process for propellers with smooth surfaces has been reported [19]. The literature available on the manufacturing of autonomous underwater vehicle (AUV) propellers and other propellers using cold forging is limited to a marine [20]. This backdrop justifies, the present study on flash-less cold forging of front and back hubs of an AUV propeller, using FEM simulation. In the simulation part, the pre-form optimization and die stress analysis was performed for the flash-less cold forging of the propeller hubs.

## II. METHODOLOGY

The methodology adopted for implementation of finite element approch for analysis of flashless cold working in AUV propeller manufacturing has been covered in this section.

### *A. Process for optimizing the pre-form*

The figure 1 shows flow diagram for optimization of work piece without under filling that starts with material selection for work-piece to achieve the flash-less forging and then develops CAD model. The model is then transferred to the FEM environment and analyzed for flash and underfill. If no flash is observed the under filling is checked for the process. If no under filling is found then process stops else process are repeated till no under filling is achieved. The flash, under filling and load are observed for both hubs by keeping one parameter constant and others varied.

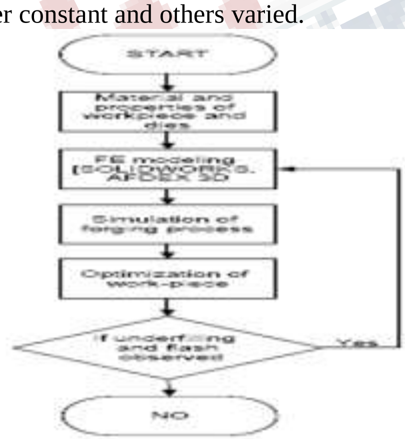


***Figure 1 Flow diagram for optimizing the work-piece***

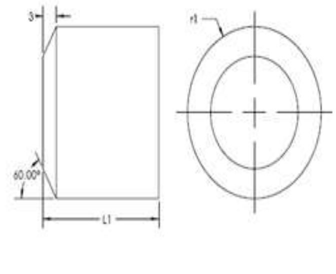

*Figure 2 Pre-form geometry of the front hub*

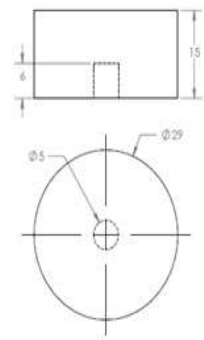

*Figure 3 Pre-form geometry of the back hub*

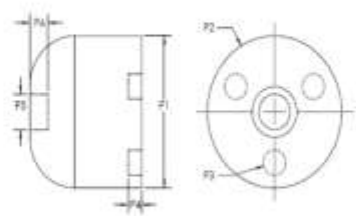

*Figure 4 Finished geometry of front hub*

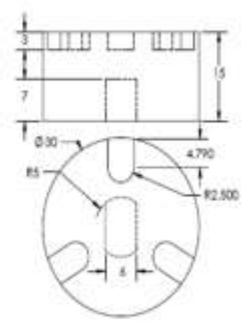

*Figure 5 Finished geometry of back hub*

### *B. Material specification and process parameters*

Using SOLIDWORKS punch, die, pre-form and finished propeller hubs were modeled as per the details shown in Figure 2, Figure 3, Figure 4, and Figure 5 to obtain the geometry in .STL file format that was later taken as an input to AFDEX simulation software. The discretization involved number of elements for punch/die as 50500 while for the work-piece 20000 elements of tetrahedral element type were used. The process parameter considered for analysis included: initial temperature of work-piece, punch and die temperature(25°C), punch velocity (250mm/s), friction co-efficient (0.33), pre-form material AA 7075 and punch/die materail AISI D2. The material properties selected for investigation as indicated in table 1 relate metal flow and die stress with respect to under-fill and flash in cold forging of propeller hubs.

 

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*Table 1 Pre-form, punch and die material properties selected for optimization studies*

| Parameter | Work-piece | Die/Punch |
|---|---|---|
| Material type | AA 7075 | AISI D2 |
| Young's modulus, GPa | 70 | 210 |
| Yield strength, MPa | 503 | 2200 |
| Poisson ratio | 0.33 | 0.33 |
| Hardness, Rockwell A, HRC | 53.5 | 62 |

### *C. Volumetric analysis*

The pre-form specifications were obtained based on the assumption that volume of finished product and initial raw material were identical [20]. The volume of finished product and pre-form specifications can be calculated theoretically through SOLIDWORKS. The next step was to obtain optimum specification of pre-form in terms of front and back hub. using AFDEX optimal pre-form was obtained varying radius r1 as indicated in figure 2 and figure 3. The iterations were performed until finished dimensions, flash and under-fill satisfactory to the specified application was achieved as shown in figure 4 and Figure5. The volumetric analysis is indicated in table 2 and table 3 for further investigation.

## III. RESULTS AND DISCUSSION

This section deals with results obtained with respect to volumetric analysis of pre-form geometry and dimensional accuracy.

### *A. Geometry Optimization of Pre-form*

**Front Hub:**

The vital concern of the present work was to eliminate under-filling and minimize flash and forge load, this objective of research was addressed through simulations using AFDEX for selected pre-form to achieve optimum pre-form geometry. The simulations indicated that due to higher volume of the pre-form considered to ensure no under filling lead to small amount of flash proportional to this excess volume. Thus with no under filling achieved resulting flash was observed and minimized as indicated in Table 2 and figure 6 for various specimens. Case I indicated deformation without any flash with about 1.36 % of under- fill. Case II resulted with 0.81% flash with under-fill and case III and IV showed deformation without under fill with respectively 2.21 % and 5.61 % of flash. The dimensional accuracy of component with various pre-form geometries were simulated and case III resulted in acceptable deviations for all geometric entities. The study concluded that case III geometry was the best option and was hence considered for further investigation.

*Table 2 AFDEX simulations for front hub pre-form*

| Cases | Diameter, mm | Pre-form volume, $(mm^3)$ | % of under-fill | % of flash |
|---|---|---|---|---|
| I | 28 | 15408.76 | 1.36% | - |
| II | 28.3 | 15748.32 | - | 0.81% |
| III | 28.5 | 15973.39 | - | 2.21% |
| IV | 29 | 16548.24 | - | 5.61% |

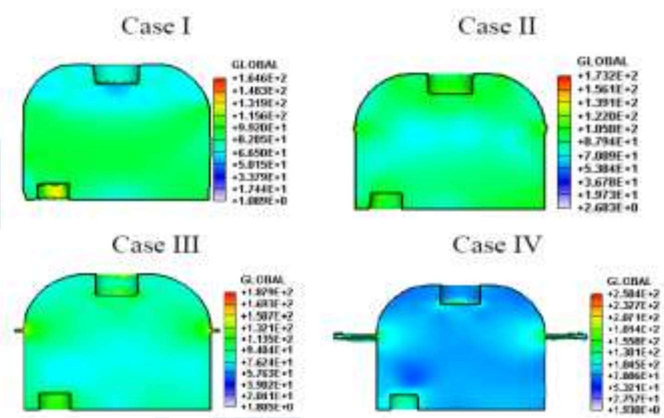


*Figure 6 Details of under-fill and flash in the cold formed front hub of AUV propeller*

**Back Hub:**

The important objective of the present work was to optimize operations that eliminated under-filling, minimize flash and forge load, that were using AFDEX on selected work-piece for optimum work-piece geometry. The simulations indicated that marginally higher volume of the work-piece compared to finished volume (9899.43 $mm^3$) ensured. The under-fill forge component indicates operations through small amount of flash proportional to the excess volume considered. The complete absence of underfill achieved resulted in flash that was minimized as indicated in Table 3 and Figure 7 for various specimens. Case I indicated deformation without any flash with 1.11 % of underfill. Case II resulted with 1.65% flash with under-fill and case III and IV showed deformation without underfill with respectively 2.99 % and 4.3 % of flash.The occurance of underfill and flash with respect to four combinations of workpiece geometries are indicated as shown in figure 7 obtained through simulations. The study concluded that case IV geometry was the best option and was hence considered for further investigation.

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*Table 3 AFDEX simulations for back hub pre-form*

| Cases | Diameter, mm | Pre-form volume, (mm³) | % of under-fill | % of flash |
|---|---|---|---|---|
| I | 29 | 9789.99 | 1.11% | - |
| II | 29.4 | 10065.19 | - | 1.65% |
| III | 29.6 | 10204.21 | - | 2.99% |
| IV | 29.8 | 10344.17 | - | 4.30% |

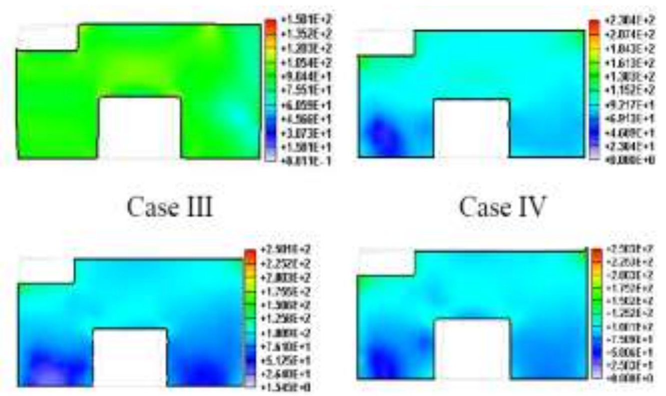


***Figure 7 Details of under-fill and flash in the cold formed***

### *B. Die stress analysis*

**Front Hub:**

The stress analysis was carried out for all four pre-forms with respect to stress distribution. It was observed that the maximum stresses occurred at front edge of the punch for case I, whereas case II, III and IV had higher stress levels at curved surface of the top ejector as shown in figure 8. It was also observed that an increase in forge load lead to increase in punch and die stress as revealed by the maximum stress magnitude of 2212 MPa observed in case III considered to be optimum pre-form as shown in figure 8. The increase in effective die stresses beyond the permissible limit of die-material leads to plastic deformation of die that affected dimensional accuracy of die and in turn the forged components. All effective die-stresses in the investigation were within allowable limit of die-material and hence the designed forge load was considered safe for the cold working process. Case IV indicated highest maximum die stress of 3759 MPa among the four simulated pre-forms. However by considering the results of section A and section B it was fulfilled that case III pre-form be taken up for further analysis.

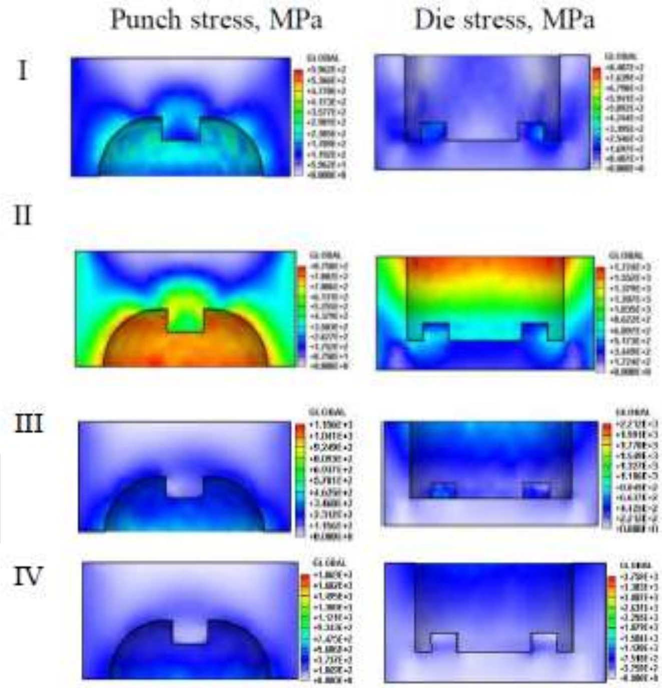


***Figure 8 Maximum punch and die stress analysis of various cases for front hub***

**Back Hub:**

The stress analysis was carried out for all four work-piece combinations with respect to stress distribution. It was observed that the maximum stress occurred at front edge of the punch for case I,whereas case II, III and IV had higher stress levels at curved surface of the top ejector as evidenced in figure 9. It was also observed that an increased in forge load led to increased punch and die stress as revealed by the maximum stress magnitude of 1669 MPa observed in case III considered to be optimum pre-form. The increase in effective die stress beyond permissible limit of die-material led to plastic deformation of die affect in dimensional accuracy of die and the forged components. All effective die-stresses in the investigation were within allowable limit of die-material and hence the designed forge load was considered safe for cold working process. Case IV indicated highest maximum die stress of 2423 MPa among the four simulated pre-forms. The geometric conformance of the case-II preform coupled with the safe stress loads in punch/die lead us to the conclusive remark to take forward case-III/IV workpiece for detailed investigation.

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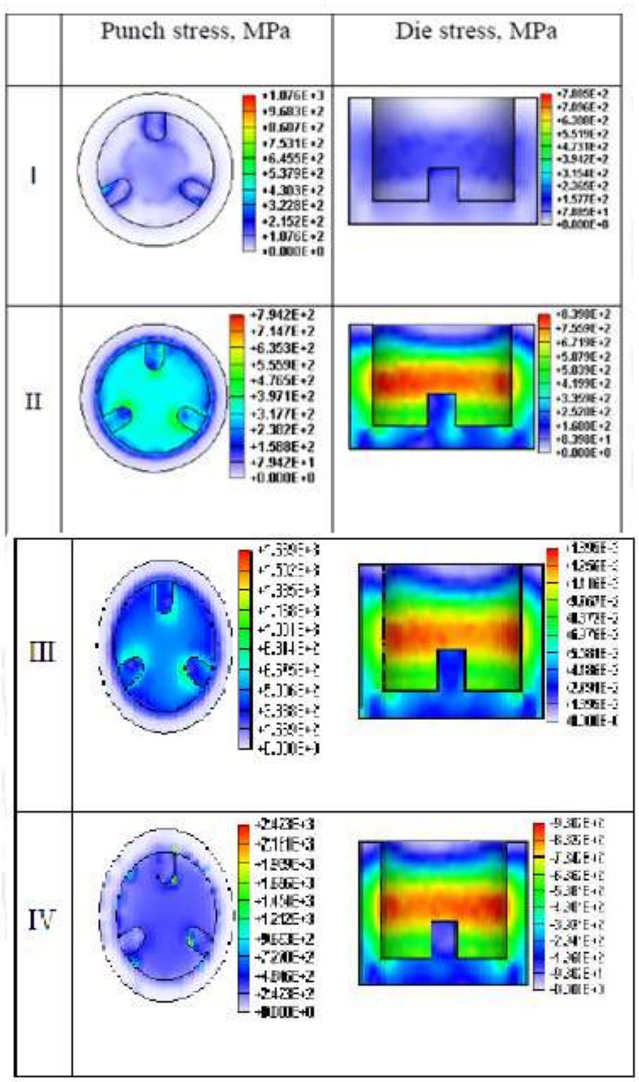


***Figure 9 Maximum punch and die stress analysis of various cases for back hub***

### *C. Comparison with AA6061 pre-form*

The design and optimization of AUV propeller front hub was carried out by cold forging considering pre-form AA 6061, the research resulted in optimal pre-form, approving geometrical deviation and permissible stress limit . However AA 6061 was less hard compared to AA 7075 in terms of hardness number. This study focused on AA 7075 material which has high strength, stress resistant, workability and improved stress-corrosion cracking resistance and highest strengths of all aluminum alloys [20]. The major enhanced mechanical properties in AA 7075 as compared with AA 6061 was hardness  Rockwell A -53.5 (40), yield strength 503Mpa (276MPa) and modulus of elasticity 70 GPa (68.9 GPa)[24]. Table 4 shows material properties on pre-form that increased when compared to AA 6061 due to high hardness and other improved mechanical properties.

***Table 4 Properties compared with AL 6061***

| Properties | AA 6061 | AA 7075 |
|---|---|---|
| Density, g/cc | 2.7 g/cc | 2.81 g/cc |
| Hardness, HRC | 40 | 53.5 |
| Ultimate Tensile Strength, MPa | 310 | 572 |
| Tensile Yield Strength, MPa | 276 | 503 |
| Modulus of Elasticity, GPa | 68.9 | 71.7 |
| Machinability | 50% | 70% |

## VI. CONCLUSION

The FE analysis of the AUV front and back hub propeller pre-form, die and punch used for cold working indicated the following observations.

1) AUV Propeller  back  hub for  Flash-less cold forging without under-fill process simulated using AFDEX FE Simulation of AA 7075, which provided useful results to obtain the most favorable pre-form shape.
2) Case III front hub and Case IV back hub were found to be favorable with respect to flash; zero under-fill and die stress among the four constant length work-pieces with different diameter were considered.
3) AA7075 declared better result as compared to AA 6061 with respect to strength, hardness, toughness and high corrosive resistance. Proposed study was a breakthrough in CAE domain  for complex geometries of propeller hub.
4)  Further potential extension to this study can cover the experimental validation, die stress analysis and optimization punch/die to enhance their life.

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