FLASH-LESS COLD FORGING AND TEMPERATURE DISTRIBUTION IN FORGED AUTONOMOUS UNDERWATER VEHICLE HUBS USING FEM ANALYSIS AND EXPERIMENTAL VALIDATION

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ABSTRACT
In this paper three-dimensional FEM analysis and experimental flashless cold forging and temperature distribution of aluminum front and back hubs of Autonomous Underwater Vehicle (AUV) propeller is presented. The rigid-plastic finite element simulation is performed using DEFORM F-3V6.0, to estimate the optimum load required for the flashless cold forging. The complex profiles of the hubs are modeled using SOLIDWORKS SP4.02007 which is used for the modeling of work-piece and die-punch assembly as well. The work-piece used is of AISI AL6061 and the die material is die steel (AISI D2). The process is optimized to form the propeller back and front hubs. For both the models, three workpieces with different aspect ratios are selected and investigated to obtain the optimum workpiece that gives flashless cold forging with acceptable underfilling. Based on the simulation results, the flash-less cold forging is successfully done on a 100 ton C-type machine. The experimental forged samples are observed in good conformity with the simulated models.

Keywords: Flashless Cold forging; Underfilling; Work-piece optimization; AUV propeller; Front and back hubs.

1. INTRODUCTION
Forging is a manufacturing process in which metal is pressed, pounded or squeezed under great pressure into high strength parts known as forgings. The process is normally (but not always) performed hot by preheating the metal to a desired temperature before it is worked. Unlike casting process, metal used to make forged parts is never melted and poured. In the area of cold forging die design and optimization, substantial investigations have been carried out by many researchers using various tools and techniques such as finite element method (FEM) artificial neural network (ANN), genetic algorithm (GA) and other computer-aided design (CAD) techniques. The works related to the current study are reviewed and presented here. Castro et al. (2004) made an attempt to obtain optimal design in forging using genetic algorithm. The design problem was formulated as an inverse problem incorporating a finite element thermal analysis model and an optimization technique conducted on the basis of an evolutionary strategy. A rigid viscoplastic flow-type formulation was adopted, valid for both hot and cold processes. The chosen design variables were work-piece preform shape and work-piece temperature. Petersen and Frederiksen (1994) presented a two-dimensional finite element analysis with special emphasis on the effects of plasticity. The geometry treated concerned a die with rather sharp fillets and the main issue was to examine stress concentration and propagation of the plastic zone in the fillet area according to the applied forging pressure. An automatic mesh generation routine was used to investigate different fillet designs and results of an optimization study were presented. The process design for closed-die forging of a bevel gear used in automobile transmission system was made by Song and Im (2007) using three-dimensional FE simulations. Process variables were the pressing type, punch location, and billet diameter. Based on the simulation results, appropriate process design without causing under-filling and folding defect was determined. Duggirala et al. (1994) introduced a method for design optimization of process variables in cold forging sequences. To minimize the possibility of the initiation of tensile fracture in the outer race preform of a constant velocity joint manufactured by cold forming operations, an adaptive Micro Genetic Algorithm was implemented. Significant reduction in the maximum damage value was achieved as a result of this optimization process. Kim et al. (2003) used rigid–plastic finite element simulation to analyze the deformation characteristic of the whole impeller hub forming processes and to optimize the process. Ohashi et al. (2003 ) developed a computer aided design system to design forging sequences and die profiles by considering forging as a procedure for adding features to a raw material, process planning as the inverse procedure, and each step of the forging process as a combination of feature eliminating processes. The system designed the forging sequences and die profiles from
the product to its raw material by eliminating features. Hussain et al. (2002) presented a used numerical study on the forming a clutch-hub using CAD simulation tool CAMP/form. Simulations for S10C steel using various die and work-piece geometries were carried out to determine the most suitable forming condition for production of the clutch-hub. Ishikawa et al. (2000) studied analytically the effects of forming stresses and generated heat on the dimensional change of punch die and work piece during forging. Im et al. (1999) introduced a design method, based on a forging simulator and commercial CAD software together with its related design system for the cold-former forging of ball joints. Lee et al. (1999) developed a CAD system using Auto-Lisp and three die-design modules namely, forward extrusion, upsetting and combined extrusion were presented. Falk et al. (1998) analyzed the applicability of different failure concepts for a closed cold forging die. The critical, process-dependent load was quantified and localized by using a finite element method. Kim et al. (1997) used three-layer neural network trained by the back-propagation algorithm to determine the initial billet geometry for the forged products using a function approximation. Xu and Rao (1997) carried out an analysis of isothermal axisymmetric spike-forging using an integrated FEM code.

Influence of different geometric parameters, processing variables and interfacial conditions on the instantaneous spike height were studied. Hsu and Lee(1997) proposed ANN based cold forging process design method suitable for shop floor to decide the cold forging process parameters for producing a sound product within the required minimum quantity of the die set. Oh et al. (1992) discussed some issues related to the simulation of cold forging operations and presented few examples to demonstrate the capability of the DEFORM system in handling cold forging problems. Meidert et al. (1992) presented a finite element (FE) based numerical modeling and physical modeling with plasticine, for process design of cold forging. A strategy was developed to allow successful 2D FE modeling of bevel gear forging and the results from the process simulation are used as load input data for a punch stress analysis. A computer-aided system called “FORMING” for designing the forming sequence for multistage forging of round parts was presented by Badawy et al. (1985). Natsume et al. (1989) performed experimental and FEM studies to understand the dimensional difference between forging tools and forged components. Lee et al. (2002) evaluated the characteristics of elastic deformation at a forming tool for a cold forged alloyed steel by experimental and FEM analysis. Qin et al. (2000) worked to combine coupled thermo-mechanical FE plastic simulation and heat transfer analysis to define heat-flux-density functions across die/work piece interfaces. Flash-less cold forging of an aluminium connecting rod was studied by Vazquez and Altan (2000) using DEFORM-FEM package. The hot forging of aerofoil blades was performed by Hu et al. (1999) who modeled smooth Bezier surfaces using Abaqus/Explicit FE software. However the attempts for cold forging of complex geometries such as propeller hubs and blades are still lacking. Against this background, we focused on flashless cold forging of the back and front hubs and blade of an AUV propeller. The work is organized in two sections; Part A deals with the front and back hubs and Part B with the blade. In this paper only Part A is presented. The three dimensional FE simulation is made by DEFORM F3 V 6.0 and geometrical modeling for the die and the work-piece is performed by SOLIDWORKS 2007 4.0.

2. MATERIALS AND METHODS

2.1 Material properties for die, punch and mountings

The material properties chosen for the current study are shown in Table 1. Aluminium is selected for the work-piece owing to its suitability for corrosive environment which is significant for underwater applications and its good formability. The Yield strength values given are all in compression. The hardness values of the components are chosen based on the working stresses.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Work piece</th>
<th>Die</th>
<th>Punch</th>
<th>Die insert</th>
<th>Plates</th>
</tr>
</thead>
<tbody>
<tr>
<td>Material type</td>
<td>AISI 6061</td>
<td>AISI D2</td>
<td>AISI D2</td>
<td>SW41</td>
<td>ASI1045</td>
</tr>
<tr>
<td>Young’s modulus(GPa)</td>
<td>70</td>
<td>210</td>
<td>210</td>
<td>210</td>
<td>210</td>
</tr>
<tr>
<td>Poission’s ratio</td>
<td>0.35</td>
<td>0.33</td>
<td>0.33</td>
<td>0.33</td>
<td>0.33</td>
</tr>
<tr>
<td>Hardness</td>
<td>HRC-24</td>
<td>HRC59.9</td>
<td>HRC-67</td>
<td>HRC-57</td>
<td>HRC-30</td>
</tr>
</tbody>
</table>

2.2 FEM Analysis

The components are modeled by SOLID WORKS SP47.2007 and assembled using assembly module and saved as STL file. Then all the STL files are imported to DEFORM-F3 3D software, run the simulation and the results are observed. If flash is occurred in the work piece, the next step is to optimize the workpiece to avoid the flash. Accordingly simulations are repeated till no flash is found. For the no flash work-piece, if effective stresses are found more than the yield then the parameters are changed till no plastic element is found. The inertia effect caused by the mass matrix is negligible even if the forging speed or the density of the material is increased to reduce the computational time (Hu et al., 1999). The velocity of the punch is 250mm/sec, friction coefficient is 0.15, initial temperature of work-piece, punch and die is 25°C, punch stroke is 14.4mm, number of steps are 100 and the step increment is 10. For the die, stress the size ratio is 3, interpolation force tolerance is 0.0001, bottom surface of the die is constrained in X, Y and Z directions, starting step number is 1, number of simulation step is 1, step increment 1, and maximum elapsed process time is 1sec. The hexahedron
elements are used for meshing; the number of elements used for work-piece is 2000, for punch 50500 and for die 50500. The simulation models for die, punch and work-piece are shown in figure 1.

![Simulation models of die and punch assembly for the back and front hubs.](image)

Figure 1 Simulation models of die and punch assembly for the back and front hubs.

### 2.3 Optimization of work-piece

The mathematical equations for the work-piece (front and back hubs) dimensions to achieve the flash-less forging are developed as follows:

It is assumed that the volume of the work-piece is equal to the volume of cavity to fill (Vazquez and Altan, 2000). Hence volume of the work pieces geometry \( V_{wp} \) and that of the final forging \( V_f \) are equated as follows:

\[
V_{wp} = V_f \quad (1)
\]

Rearranging the terms and substituting the values final dimensions of the workpiece, the equation reduces to:

\[
\pi r_1^2 L_1 = V_f - \sum_{i=1}^{n} V_c 
\]

\[
L_1 = \frac{V_f - \sum_{i=1}^{n} V_c}{\pi r_1^2} 
\]

(2)

The required dimensions of the final cold-forged hubs according to equation (3) are shown in Figure 2. The optimized model is then transferred to the FEM environment, and analyzed for flash. If no flash is observed then under filling is checked for the process. If no under - filling is found then stops the process, otherwise the process is repeated till no under-filling is achieved.

### 2.4 Finite element formulation

In cold forging elastic deformation can be neglected and the material is considered as rigid plastic. In this study the rigid-plastic finite element method is applied for analysis of deformation.

The basic equations of the rigid–plastic finite element are as follows (Kim et al., 2003):

**Equilibrium equation:**

\[
\sigma_{ij} = 0 \quad (4)
\]

**Compatibility and incompressibility condition:**

\[
\dot{\varepsilon}_{ij} = \frac{1}{2} (\dot{u}_i + \dot{u}_j) \quad \dot{\varepsilon}_v = \dot{u}_r = 0 \quad (5)
\]

**Constitutive equations:**

\[
\sigma'_{ij} = \frac{2}{3 \bar{\varepsilon}} \dot{\varepsilon}_{ij} \quad \bar{\sigma} = \sqrt{\frac{3}{2} \left( \sigma'_{ij} \sigma'_{ij} \right) \dot{\varepsilon}_{ij} \dot{\varepsilon}_{ij}} \quad (6)
\]

**Boundary conditions:**

\[
\sigma_{ri} = F_j \text{ on } S_F, \quad u_i = U_i \text{ on } S_U
\]

where \( \sigma_{ij} \) and \( \dot{\varepsilon}_{ij} \) are the stress and the strain velocity, respectively. \( \bar{\sigma} \) and \( \dot{\varepsilon} \) are the effective stress and the effective strain velocity, respectively. \( F_j \) denotes the force on the boundary surface of \( S_F \) and \( U_i \) denotes the deformation velocity on the boundary surface of \( S_U \).

![Dimensions of the optimized work-pieces.](image)

Figure 2 Dimensions of the optimized work-pieces (all dimensions in mm)

The basic mathematical equations are as follows (Song and Im, 2007):

\[
\Pi = \int \bar{\sigma} \dot{\varepsilon} dV - \int_{S_F} t_i v_i dS 
\]

where \( \Pi \) is functional for rigid-plastic material, \( \bar{\sigma} \) is the effective stress, \( \dot{\varepsilon} \) is effective strain rate, \( t_i \) is the traction specified on the boundary, \( s, U_i \) is the velocity component.

\[
\delta \Pi = \int v_i \delta \dot{\varepsilon} dV - \int_{S_F} t_i \delta v_i dS + K \int v_i \delta \varepsilon_i dV = 0
\]

(9)

By introducing the penalty constant \( K \) and modifying the functional equation (Eq (9)) the incompressibility constraint on admissible velocity fields may be removed. \( \delta \dot{\varepsilon} \) is the arbitrary variation and \( \delta \dot{\varepsilon} \) and \( \delta \varepsilon_{ij} \) are variations in strain rate from \( \delta U_j \). Equation (9) can be converted to non linear algebraic equation by using finite element descritization.
Using numerical technique like Newton-Raphson, the solution for nonlinear simultaneous equations can be obtained.

**Aspect ratio**

For the purpose of workpiece optimization, aspect ratios are individually defined for front and back hubs, as follows.

Aspect ratio for front hub, \( (AR)_F = \frac{\text{Diameter of workpiece}}{\text{Height}} \)  

Aspect ratio for back hub, \( (AR)_B = \frac{\text{Diameter of workpiece}}{\text{Diameter of hole}} \)

3. **SIMULATION RESULTS DISCUSSION**

3.1 **Temperature distribution**

3.1.1 **Front hub**

The maximum temperature is observed for the front hub at the bottom surfaces of the blind holes and the minimum at the centre of front hub as shown in Figure 3. The temperature varies during the forging process at the different points of the forged front hub and the temperature variation from \( 0^\circ \text{C} \) to maximum with respect to time is shown in Figure 4.

3.1.2 **Back hub**

The maximum temperature is observed for the back hub at the bottom surface of the blind capsule hole and the minimum towards radius of back hub as shown in Figure 5. The temperature varies during the forging process at the different points of the forged back hub and the temperature variation from \( 0^\circ \text{C} \) to maximum with respect to time is shown in Figure 6.
and the top hole are desirable to act as fillets. Hence it is concluded that case II is the optimum work-piece. The results are summarized in Table 2.

Figure 7 Cross section view of front hub formation for case I

Figure 8 Cross section view of front hub formation for case II

Figure 9 Cross section view of front hub formation for case III

Table 2 Work-piece volume, flash volume and percentage flash of front hub for various aspect ratios

<table>
<thead>
<tr>
<th>Cases</th>
<th>(AR)_f</th>
<th>Work-piece volume (mm³)</th>
<th>Flash volume (mm³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>0.961</td>
<td>12437.57</td>
<td>No flash</td>
</tr>
<tr>
<td>II</td>
<td>1.038</td>
<td>14317.91</td>
<td>No flash</td>
</tr>
<tr>
<td>III</td>
<td>1.115</td>
<td>16937.74</td>
<td>1318.51</td>
</tr>
</tbody>
</table>

3.2.2 Back hub

The under-filling and flash are observed for the back hub, for three different aspect ratios (AR)_B 5.80, 5.31 and 5.90 (Cases I, II and III respectively). Figures 10, 11 and 12 show sectional views of the corresponding forged models. For all the cases under-filling is observed at the bottom corners and for case I, at the side walls of die insert as well; but these are well within the tolerable limit. Since we are interested in flashless forging, Case I seems the best option as it has the minimum flash as evident from Figure 7 and Table 3. Moreover no extra trimming operation is needed to remove this flash because the forged back hub has to be drilled at the location of the flash.

Table 3 Work-piece volume, flash volume and percentage flash of back hub for various aspect ratios

<table>
<thead>
<tr>
<th>Cases</th>
<th>(AR)_B</th>
<th>Work-piece volume (mm³)</th>
<th>Flash volume (mm³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>5.80</td>
<td>9789.99</td>
<td>570.82</td>
</tr>
<tr>
<td>II</td>
<td>5.31</td>
<td>10040.45</td>
<td>821.28</td>
</tr>
<tr>
<td>III</td>
<td>5.90</td>
<td>10344.17</td>
<td>1125</td>
</tr>
</tbody>
</table>

Figure 10 Cross section view of back hub formation for case I

Figure 11 Cross section view of back hub formation for case II
3.2.3 Effect of aspect ratio on forging load
Tables 3 and 4 show the predicted forging loads and effective stresses with respect to the stroke length of the punch under various aspect ratios for the front and back hubs. For the front hub, the maximum forging load is found to be for the case III \((1.5 \times 10^6 \text{ N})\). The load goes on reducing with decrease in aspect ratio as shown in Table 2. The required load to form the front hub from the case I is the least \((1.08 \times 10^5 \text{ N})\) but under filling is the worst as already seen. Thus when comes to a trade-off between forging load and flash, case II turns out to be the best. In the case of back hub the minimum value of forging load for case I \((1.2 \times 10^5 \text{ N})\) substantiates its choice in section III.A.b. as the optimum model.

Table 4 Load prediction and effective stresses of front hub for various aspect ratios

<table>
<thead>
<tr>
<th>Case (AR)</th>
<th>Load prediction in N</th>
<th>Effective stress</th>
</tr>
</thead>
<tbody>
<tr>
<td>I 0.961</td>
<td>1.08 \times 10^5</td>
<td>373 MPa</td>
</tr>
<tr>
<td>II 1.038</td>
<td>2.21 \times 10^5</td>
<td>421 MPa</td>
</tr>
<tr>
<td>III 1.115</td>
<td>1.5 \times 10^6</td>
<td>441 MPa</td>
</tr>
</tbody>
</table>

Table 5 Load prediction and effective stresses of back hub for various aspect ratios

<table>
<thead>
<tr>
<th>Case (AR)</th>
<th>Load prediction in N</th>
<th>Effective stress</th>
</tr>
</thead>
<tbody>
<tr>
<td>I 5.80</td>
<td>1.2 \times 10^5</td>
<td>443</td>
</tr>
<tr>
<td>II 5.31</td>
<td>1.59 \times 10^5</td>
<td>461</td>
</tr>
<tr>
<td>III 5.90</td>
<td>3.37 \times 10^5</td>
<td>468</td>
</tr>
</tbody>
</table>

3.3 Experimental setup
For the experimental work 100 tonn C-type forging machine as shown in Figure 13 is used. Different amounts of deformation are obtained by altering the shut height of the press. The machine is run at the speed of 250 mm/sec. The die and punch are aligned at the same axis. The machine specifications are summarized in Table 6.

Table 6 Machine specifications

<table>
<thead>
<tr>
<th>Item</th>
<th>Specification</th>
</tr>
</thead>
<tbody>
<tr>
<td>Type</td>
<td>Single strike, Continuous stroke</td>
</tr>
<tr>
<td>Model</td>
<td>J23</td>
</tr>
<tr>
<td>Capacity</td>
<td>1000 KN</td>
</tr>
<tr>
<td>RPM</td>
<td>1455 rpm</td>
</tr>
<tr>
<td>Valve pressure</td>
<td>0.2-1 MPa</td>
</tr>
<tr>
<td>Frequency</td>
<td>50Hz</td>
</tr>
<tr>
<td>Electrical data</td>
<td>380V, 55A, 3 \sim 50Hz</td>
</tr>
</tbody>
</table>

4. EXPERIMENTAL RESULTS
4.1 Underfilling and Flash
4.1.1 Front hub
Based on the simulation, the front and back hub have been cold forged for different aspect ratios and the underfilling, flash and dimensional accuracy are compared with the simulated models. Figure 14 shows the the experimental forged samples of the front hub for cases I, II and III. Exactly similar to the predictions, case II is observed to be the best, as it has acceptable underfilling and no flash. Table 6 shows the comparison of the required and experimental dimensions of the front hub for cases I, II and III. It is observed that the case III has the best dimensional accuracy, but there is problem of flash as already seen in the simulation (Figure 9) and experimentally proved in Figure 10. Hence the next option is Case II which has no flash and acceptable dimensional error.

4.1.2 Back hub
The required dimensions (design values) of different parts of the back hub are illustrated in Figure 15. In order to achieve
this final model, the workpiece has been optimized by FEM simulation and compared with the experiment. Figure 16 shows the experimental forged samples of the back hub for cases I, II and III. Exactly similar to the predictions, case I is observed to be the best, as it has acceptable underfilling and minimum flash. This finding is consistent with the dimensional analysis provided in Table 7 which shows that Case I has the minimum dimensional error. It is worth noting that the capsule shaped hole at the bottom of the back hub as shown in Figure 17 is also formed in a single operation. In this case too, the experimental results are in good agreement with the predictions.

### Table 6 Comparison of designed and experimental dimensions of front hub

<table>
<thead>
<tr>
<th>Case (AR)</th>
<th>Diameter in mm</th>
<th>Height in mm</th>
<th>Required</th>
<th>Forged</th>
<th>%Err</th>
<th>Required</th>
<th>Forged</th>
<th>%Err</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>0.96</td>
<td>30</td>
<td>29.2</td>
<td>25</td>
<td>2.37</td>
<td>23.7</td>
<td>5.04</td>
<td></td>
</tr>
<tr>
<td>II</td>
<td>1.03</td>
<td>30</td>
<td>30.1</td>
<td>25</td>
<td>0.60</td>
<td>23.6</td>
<td>5.44</td>
<td></td>
</tr>
<tr>
<td>III</td>
<td>1.11</td>
<td>30</td>
<td>30.1</td>
<td>25</td>
<td>0.53</td>
<td>24.4</td>
<td>2.32</td>
<td></td>
</tr>
</tbody>
</table>
Table 7 Comparison of designed and experimental dimensions of back hub

<table>
<thead>
<tr>
<th>Parameter</th>
<th>OD</th>
<th>a</th>
<th>b</th>
<th>c</th>
<th>d</th>
<th>E</th>
</tr>
</thead>
<tbody>
<tr>
<td>Required Dimensions (mm)</td>
<td>30.0</td>
<td>6.00</td>
<td>10.0</td>
<td>5.00</td>
<td>15.0</td>
<td>15.0</td>
</tr>
<tr>
<td>Case I</td>
<td>Forged</td>
<td>29.2</td>
<td>6.04</td>
<td>09.9</td>
<td>5.05</td>
<td>14.8</td>
</tr>
<tr>
<td>(AR)_h=5.31</td>
<td>%Error</td>
<td>2.36</td>
<td>0.67</td>
<td>0.50</td>
<td>01.00</td>
<td>01.00</td>
</tr>
<tr>
<td>Case II</td>
<td>Forged</td>
<td>29.6</td>
<td>06.1</td>
<td>10.1</td>
<td>05.0</td>
<td>14.9</td>
</tr>
<tr>
<td>(AR)_h=5.80</td>
<td>%Error</td>
<td>01.2</td>
<td>02.3</td>
<td>01.7</td>
<td>01.8</td>
<td>00.2</td>
</tr>
<tr>
<td>Case III</td>
<td>Forged</td>
<td>29.8</td>
<td>06.0</td>
<td>09.9</td>
<td>04.9</td>
<td>15.0</td>
</tr>
<tr>
<td>(AR)_h=5.90</td>
<td>%Error</td>
<td>00.3</td>
<td>00.1</td>
<td>00.60</td>
<td>00.80</td>
<td>00.46</td>
</tr>
</tbody>
</table>

*Outside diameter of the final product, @ Refer figure 10

5. CONCLUSION

The FEM analysis and experiments for flashless cold forging and temperature distribution of front and back hubs of AUV propeller have been performed successfully. The next part of the current study is focused on the formation of blade. The simulation results are in good agreement with the experiments. The handling of complex geometries especially for cold forging, the workpiece optimization, detailed numerical analysis and strong experimental results are contributions in this work. Stress analysis considering thermal stresses of puncher and ejector of front and back hubs, optimization of die design using numerical and experimental methods to reduce the overall cost of production are few of the potential future works.

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