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FEM SIMULATION AND EXPERIMENTAL VALIDATION OF FLASH-LESS COLD FORGING FOR PRODUCING AUV PROPELLER BLADE*

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Abstract– Manufacturing of the Autonomous Underwater Vehicle (AUV) is a challenge for researchers because of the hazardous ocean environment. The propeller is the most complex part in AUV because of its elaborately shaped blade designed to increase the thrust. The selection of the manufacturing process, flash-less cold forging die design and optimization of the work-piece are the major issues to reduce the overall cost of the propeller. Numerous investigations have been carried out in this area by many researchers using various tools and techniques. However, cold forging of complex geometries such as the propeller blade is still lacking. Moreover, volumetric analysis and optimization of work-piece have not been reported so far for complex geometries. In this work, the cold forging process is adopted to produce the propeller blade. Three-dimensional finite element (FE) analysis and experimental flash-less cold forging of aluminum blade of the AUV propeller is presented. The work-piece used is of AISI AL6061 and the die material is die steel (AISI D2).Based on the simulation results, the flash-less cold forging is successfully done on a 100 ton C-type machine.

Keywords– Autonomous under water vehicle, cold forging, FEM, flash-less, under-filling

1. INTRODUCTION

Autonomous underwater vehicle (AUV) is an unmanned, tether-free vehicle which is powered by battery or fuel cell [1]. The direction of AUV is controlled by preprogrammed computers utilizing various navigation sensors such as inertial measurement unit, sonar sensor, laser ranger, pressure sensor, etc. Research on AUV has become very important and there has been increased interest as well among the marine researchers in the last two decades. The demand in the current market is tremendous for AUV; hence researchers are working to fulfil this requirement.

It is reported that in the 1990s, 30 AUVs were developed by researchers around the world [2]. Because of its ability to do the task independently, researchers have used it for various applications such as ecology survey and sea bed mapping. It has been reported by many researchers that AUV could be used successfully in hazardous conditions like Deep Ocean [2]. The AUV system is an integration of some essential subsystems. Propulsion system is one of these subsystems. In practice, the propulsion system of AUV contains a propeller and an electric motor (Marsh 2004) [3].Some researchers have determined the aspect ratios that fill the die cavity using FEM and neural networks, but have not discussed flash [4]. Similarly, [5] and [6] also worked on no under filling and flash-less forging. No under filling and no folding lead to net shape forging. Tomov and [7] presented the net shape forging, but did not report the

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flash minimization. For propeller blades, achieving net shape without flash is difficult. The hot forging of aerofoil blades was performed by Hu et al [8], who modeled smooth Bezier surfaces using Abaqus/Explicit FE software. They measured aerofoil blade flash at several regions and found the flash ranging from 40%-90% at various regions, and thus caused a greater wastage of material. The flash-less cold forging is defined as the one in which the amount of flash is minimal.Similar work has been done by [9-15].

Even though many researchers have focused on various manufacturing processes to produce the AUV propeller, like machining, casting, injection molding and hot forging, an attempt for cold forging of complex geometries such as AUV propeller blades has not been reported. Optimization of the work-piece to achieve flash-less forging for complex profile and stress analysis of induced stresses is to be studied thoroughly. Moreover, research is required to be done in die design, especially cold forging die because the die will undergo high loads; hence it has to undergo stress analysis. The work-piece has to be optimized for forging the propeller blade for flash-less forging with no under filling to increase the die life, to reduce the number of operations and to obtain dimensional accuracy. Predominant complexity in the propeller blade is hydrodynamic profile and twist because it is very troublesome to achieve the flash-less forging, especially in cold forging.

Approaches: The study was carried out to analyze the process and design the cold forging die as per the dimension of the designed geometry, by using FEM technique and experimental analysis; SOLID WORKS and DEFORM-F3 software are used for design and for analysis respectively. The optimization of pre-form for the propeller blade was done by varying the design parameter. Experimental method has also been used to validate simulation results.

2. OPTIMIZATION OF WORK-PIECE FOR FRONT HUB

Figure 1 shows the flow diagram for the whole process of optimization of work piece without under filling. It starts with developing the mathematical equation for the work-piece to achieve the flash-less forging and then develops the CAD model of the work-piece. This model is then transferred to the FEM environment and analyzed for flash. If no flash is observed the under filling is then checked for the process. If no under filling is found then stop the process, otherwise the process is repeated till no under filling is achieved. The flash, under filling and load is observed for hubs and blade by keeping one parameter constant and the others varied. In the case of the blade, the flash and under filling are studied for pre-form 1 by keeping the area constant, and the thickness of the work-piece is varied. For pre-form 2 the thickness of the work-piece is kept constant and the area is varied. Further, for pre-form 3 flash thicknesses are varied, and the area and thickness of the work-piece are kept constant.

3. RESULTS AND DISCUSSION

In this section the under filling and flash are studied for the blade. The pre-forms, Pre-form 1 and Pre-form 2, are tested and the under filling and flash are observed for five different values of work-piece thickness t_{wp} (cases I, II, III, IV and V respectively) and the results are summarized in Table 1. The work-piece volume, observed flash and under filling are noticed from DEFORM. The flash volume is observed from the DEFORM for case I, II and III, since both under filling flash occur. For case IV and V no under filling is observed, hence the flash volume is calculated by subtracting the designed volume from the work-piece volume.

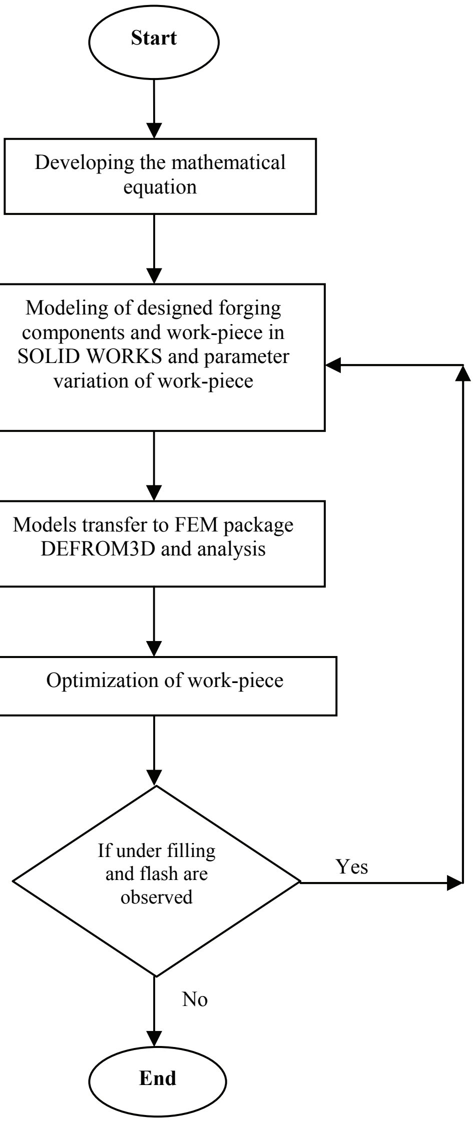


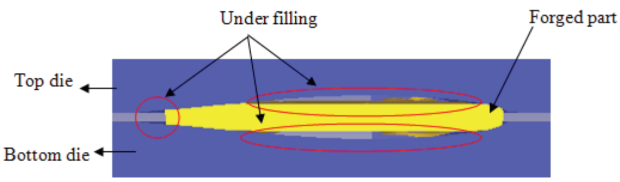
Fig. 1. Flow diagram for optimizing the work-piece

Table 1. Work-piece volume, flash volume, under filling volume and design volume of Pre-form 1 for various thicknesses when A_{wp}= 626.72 mm^2 flash thickness t_f = 0.5mm

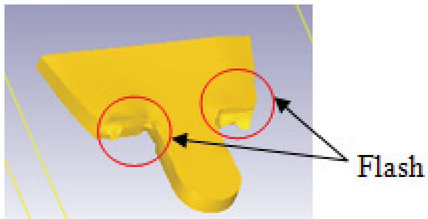
Cases	t_{wp} (mm)	Work-piece volume (mm^3) DEFORM	Flash volume for no under filling (mm^3)	Designed volume (mm^3)	Observed flash	Under filling
I	1.5	938.49	Flash with under filling	822.29	Less	More
II	2.0	1251.46	Flash with under filling	822.29	Less	Medium
III	2.5	1564.45	Flash with under filling	822.29	Medium	Less
IV	3.0	1877.43	1055.14	822.29	More	No under filling
V	3.5	2189.79	1367.5	822.29	More	No under filling

Figures 2-6 show the sectional views of the respective simulated forged models for Pre-form1. For case I, case II and case III, a slight under filling is observed at the top and bottom side of the cavities.

However, for case I, the flash is observed at the back side of the blade as shown in Fig. 2b, and under filling is observed at the top and left side of the flash zone too as evident from Fig. 2a. For case IV, no under filling is found but a flash of 1055.14mm^3 (Table 1) is observed at the flash zone as shown in Figure 4.14. Hence it is concluded that optimum thickness is 3mm to achieve no under filling.



(a)



(b)

Fig. 2. Case I cross section view along the width (a) flash at back side(b) of pre-form 1

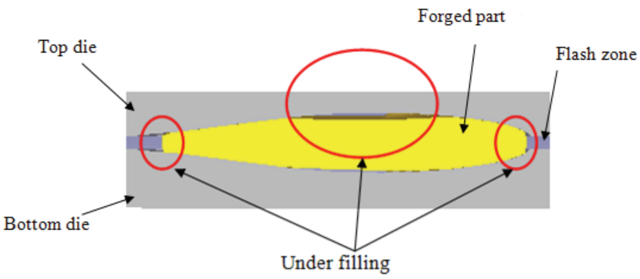


Fig. 3. Case II cross section view of pre-form 1 along the width

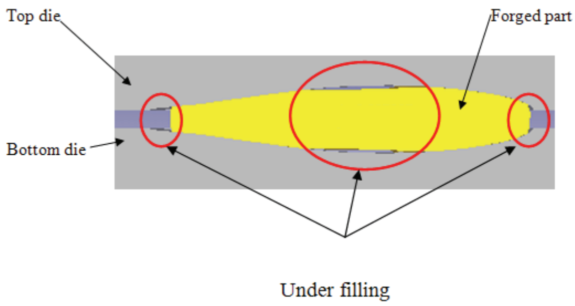


Fig. 4. Case III cross section view of pre-form 1 along the width

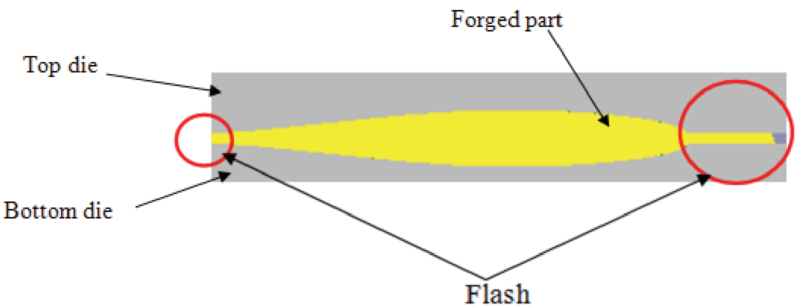


Fig. 5. Case IV cross section view of pre-form 1 along the width

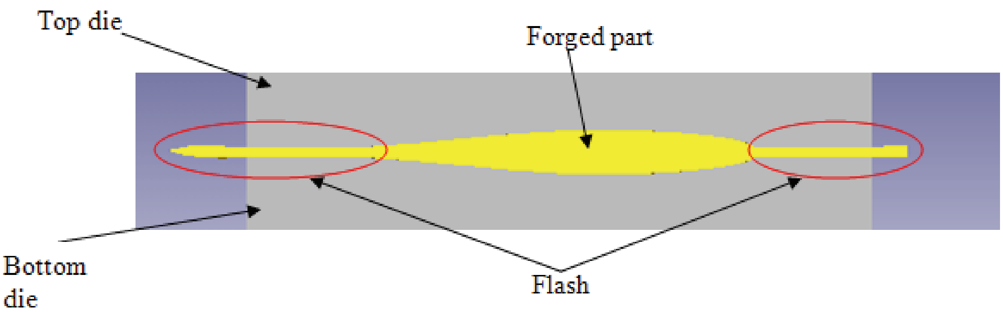
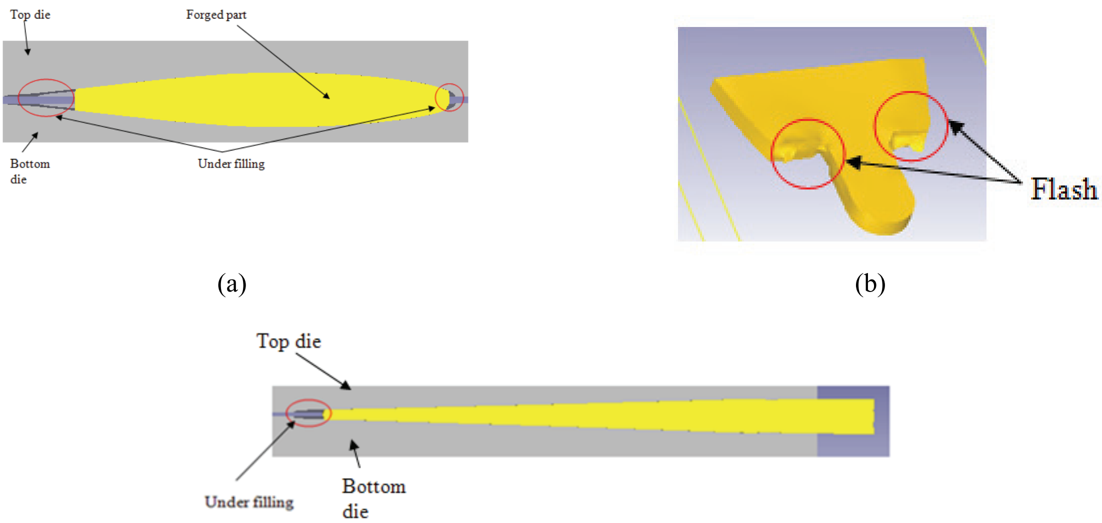


Fig. 6. Case V cross section view of pre-form 1 along the width

However, there is a flash which is to be minimized by varying work-piece area A_{wp} as mentioned in Section 3.3. For this purpose, Pre-form 2 is made with a reduced A_{wp} and tested for five different A_{wp} (cases I, II, III, IV and V) and the results are tabulated in Table 2. Figures, 7-11 show the sectional views of the simulated models of Pre-form 2 for the five cases. For case I under filling is observed at the left and right flash zones and at the left side flash zone of the section along the length as well, as shown in Figure 7a, 7c. The flash is observed at the back side of the tail end as shown in Fig. 7b. For case II, less under filling is observed at the left side of the section along the length and flash is observed at the left and right side of section along the width and at the right side of the section along the length as shown in Fig. 8a and b. For the case III, IV and V no under filling is observed but the flash is observed at the left and right side flash zone of the section along the width and section along the length as shown in Figs. 9-11. It is observed that as the area is increased the flash increases and under filling decreases. Table 4.6 depicts the work-piece volume, flash volume, percentage of flash and under filling. The observed flash and under filling are categorized as less, medium and more. The flash volume is calculated for no under filling cases and for the cases where the flash and under filling are observed together, the observed flash and under filling are stated from the DEFORM as shown in Figs. 7 and 8. For no under filling cases, the flash volume is calculated by subtracting the designed volume from work-piece volume. It is observed that the under filling is maximum for case I. Since we are interested in flash-less forging, Case III seems to be the best option as it has the minimum flash as evident from Fig. 9 (case III) and Table 2. Moreover, no extra trimming operation is needed to remove this flash.

Table 2. Work-piece volume, flash volume and designed volume of Pre-form 2 for various area A_{wp} flash thickness $t_f = 0.5mm$ and Work-piece thickness $t_{wp} = 3mm$

Cases	A_{wp} (mm^2)	Work-piece volume (mm^3) DEFORM	Designed volume (mm^3) DEFORM	Flash volume (mm^3)	Observed flash	Under filling
I	342.21	953.18	822.29	Less	Less	More
II	352.34	984.39	822.29	Less	Less	Medium
III	377.90	1055.86	822.29	233.57	Medium	No under filling
IV	426.14	1275.52	822.29	453.23	More	No under filling
V	431.55	1291.70	822.29	469.41	More	No under filling



(a) (b)

(c)

Fig. 7. Case I cross section view along the width (a), tail side isometric view (b) and along length(c) of pre-form 2

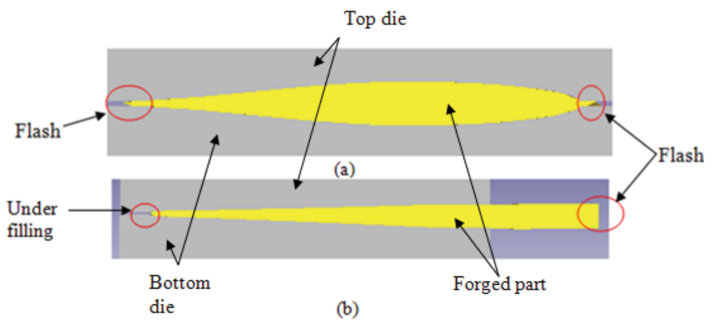
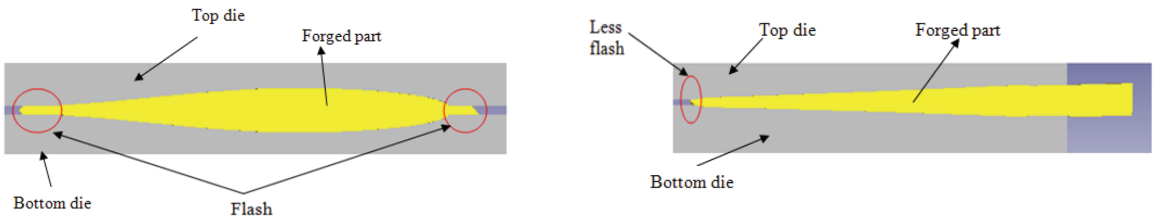
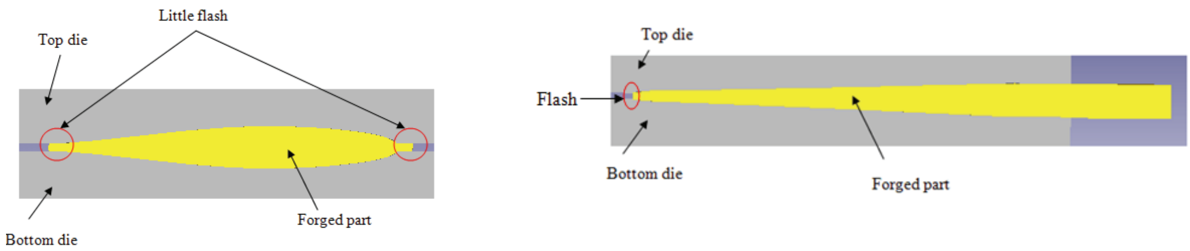


Fig. 8. Case II cross section view along the width (a) and along length(b) of pre-form 2



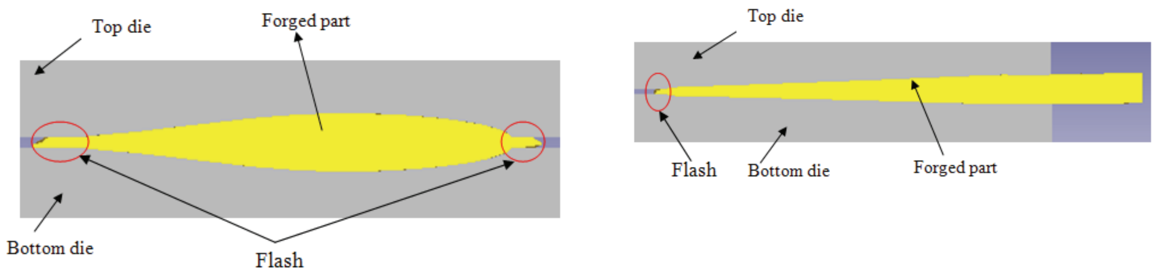
(a) (b)

Fig. 9. Case III cross section view along the width (a) and along length(b) of pre-form 2



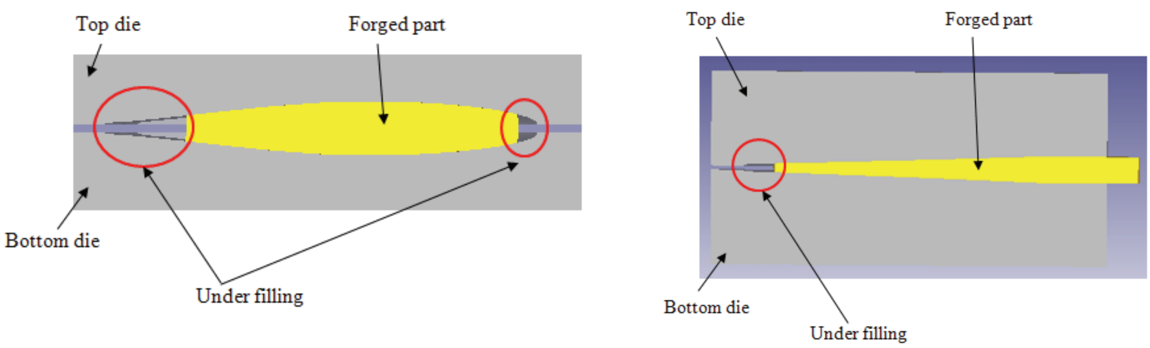
(a) (b)

Fig. 10. Case IV cross section view along the width (a) and along length(b) of pre-form 2



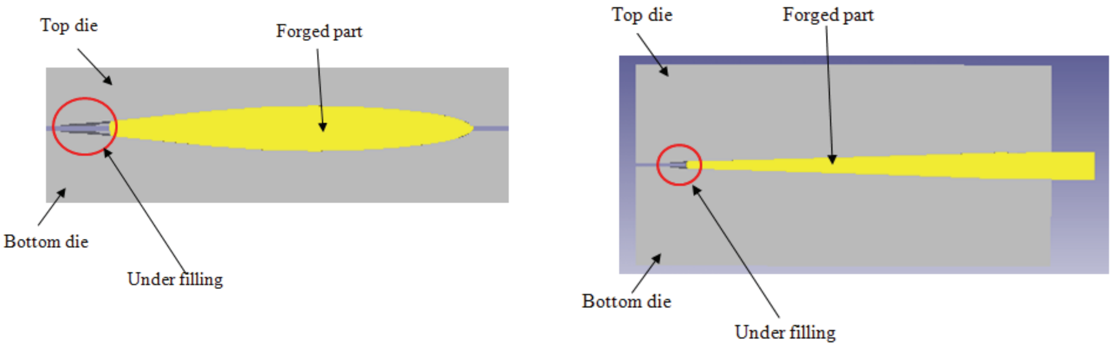
(a) (b)

Fig. 11. Case V cross section view along the width (a) and along length(b) of pre-form 2



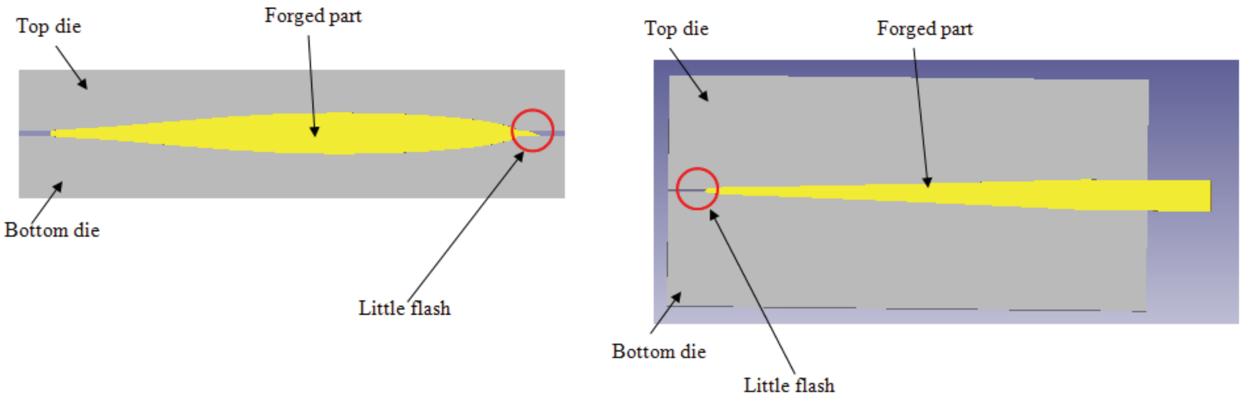
(a) (b)

Fig. 12. Case I cross section view along the width (a) and along length(b) of pre-form 3



(a) (b)

Fig. 13. Case II Cross section view along the width (a) and along length(b) of pre-form 3



(a) (b)

Fig. 14. Case III Cross section view along the width (a) and along length(b) of pre-form 3

Table 3. Work-piece volume, flash volume and flash percentage of Pre-form 3 for various flash thicknesses t_f with area A_{wp} = 342.21mm^{2}and thickness t_{wp}=3mm

Cases	Flash Thickness t_f (mm)	Work-piece volume (mm^3) DEFORM	Flash volume (mm^3)	Under filling along the length	Under filling along the width	Flash volume (%)
I	0.5	1055.86	Less	More	More	Less
II	0.3	1055.86	Medium	Medium	Medium	Medium
III	0.2	1055.86	233.57	No under filling	No under filling	13.72

However, for Pre-form 2, the reduction in work-piece volume was 1877.43mm^3 to 1055.86mm^3. The percentage is calculated from the ratio of the flash volume to the work-piece volume for the no under filling. For the pre-form 1 the percentage of flash for no under filling was 56.20% and for pre-form 2 is 22.12%. Further, the study is continued with the Pre-form 3 to reduce the flash with no under filling. The pre-form, Pre-form 3 is tested and the under filling and flash are observed for three different values of flash thickness t_f (cases I, II and III respectively) and the results are summarized in Table 3. The area and work-piece thickness are kept constant and under filling is observed by simulation. The under filling is categorized into three stages namely more, medium and less under filling. At the same time, the flash volume is calculated by subtracting the designed volume from initial work-piece volume if no under filling is observed and the percentage is calculated from that volume for the optimum cases. Figures 12-14 show the sectional views along the length and along the width of the respective simulated forged models for Pre-form 3. For case I, under filling is observed at the left and right side cavities of the section along the width of the blade and left side cavity in the section along the length of the blade as is evident from Fig. 12.

However for case II, under filling is observed only at the left side cavities of both sections along the width and along the length of the blade. This is evident from Fig. 13. For case III, no under filling is found in either section but a flash is observed at the right side of the section along the width of the blade as described in Table 4.7, and is observed at the flash zone as shown in Fig. 13. Hence it is concluded that optimum pre-form thickness is 3mm and flash thickness t_f is 0.2mm to achieve no under filling at the top and bottom side of the section along the width of the blade and left side of the section along the length of the blade. Since the interest of the present study is flash-less forging, Case III seems to be the best option as it has a minimum flash of 13.72% as evident from Fig. 13 case III and Table 3. Moreover, no extra trimming operation is needed to remove this flash. Table 4 shows comparison of the designed and simulated dimensions of the blade. The simulated optimum blade is compared with the designed blade. It is evident that deviation for all the dimensions is within the tolerable limit.

Table 4. Comparison of designed and DEFORM dimensions of blade

Dimension		41.06	20.48	0.30	7.21	4.01	8.81
Tolerance (mm)		±0.25	±0.25	±0.1	±0.25	±0.15	±0.15
	DEFORM	41.20	20.44	0.37	7.43	4.18	8.95
	Deviation	0.20	0.04	0.03	0.03	0.02	0.14

4. EXPERIMENTATION

Based on FEM simulations, the blade is cold forged in five stages which are similar to those performed in the simulation and the results are compared. Figures 15a-e depict the forged blade for the five stages. It is observed that the experimental results are quite similar to the simulated results. Based on the simulation, the Pre-form1 is cold forged for different t_{wp} and the under filling, flash and dimensional accuracy are compared with the simulated models. Figure 16 depicts the dimensions of the designed shape of the blade. The dimensional errors for this case are also within the tolerable limit, as illustrated in Table 5. The data is obtained from the measurement of some major parameters, since some of the parameters were very difficult to measure like variation of volume in all points. Hence, some of the parameters measured are shown in Fig. 16, which depicts the front and back views of the blade to specify the twist height of the blade. Figure 17 depicts the blade for the second stage of the forging process for different thicknesses of pre-form 1 (2, 2.5 and 3mm), which are studied to achieve the flash-less forging experimentally. Figure 17 shows the under filling occurred after forging for the thicknesses 2 and 2.5mm of the pre-form 1. It is observed that, as the thickness reduces the flash reduces and the under filling increases, and as thickness increases the flash increases and under filling reduces. For the thickness 3mm, no under filling is observed and flash occurred. For thickness of 2mm and 2.5mm, forming is carried out up to the second stage and the under filling is observed, which reduces the efficiency of the propeller. For 3mm thickness, all stages are performed and the flash thickness of 0.5mm is maintained.

This indicates that the experimental forged samples of the Pre-form1 for cases II, III and IV are exactly similar to the predictions, case IV shows no under filling but flash. Accordingly, only case IV is tested experimentally for Pre-form 3 and the results are found extremely similar to the simulated ones. However, one stage(c- trimming), as discussed in the simulation steps is reduced in this case since very little flash occurred. The required thickness (0.3mm) was impossible to obtain by using Pre-form1 and this problem was rectified by using Pre-form 3 Case III, which therefore is found to be the optimum, as evident from simulation as well. The measured dimension of thickness 0.34mm obtained from Pre-form 3 is as shown in Fig. 19. Figures 18a-d depict the forged blade for the four stages for pre-form 3. Table 6 and 7 shows the flash and under filling volumes for un-optimized and optimized work-piece. It is observed that the minimum deviation from basic size is 0.04mm and the maximum is 0.15mm. The under filling and flash are calculated as stated in Section 4.6.2. The Table 4.6 shows that as thickness increases under filling reduced and flash is increased. It is evident from Table 7 that the flash is minimum for pre-form 3 which is 39.17mm^3 with no under filling.

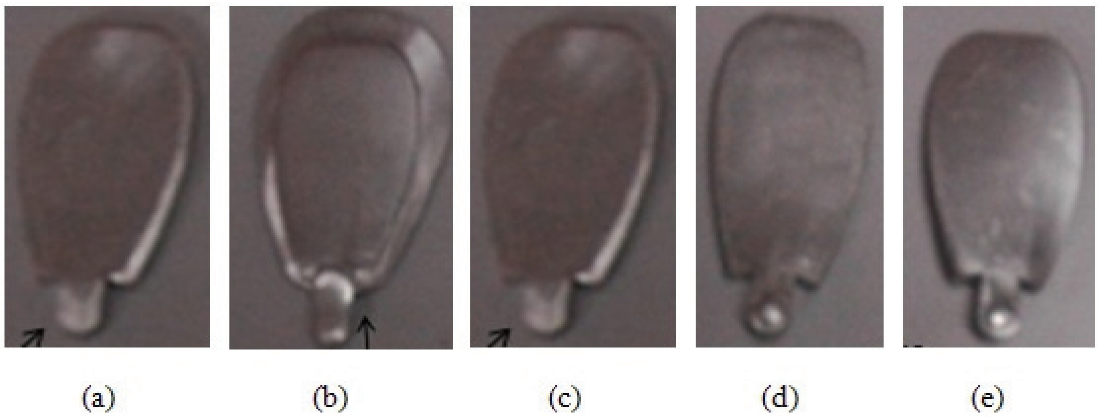


Fig. 15. Five stages to forge propeller blade by pre-form 1

Table 5. Comparison of designed and experimental dimensions of blade

Dimension (mm)	41.06	20.48	0.30	7.21	4.01	8.81
Designed tolerance (mm)	±0.25	±0.25	±0.05	±0.15	±0.1	±0.15
Experimental (mm)	41.10	20.60	0.34	7.11	4.05	8.96
Deviation(mm)	0.21	0. 12	0.04	0.90	0.04	0.15

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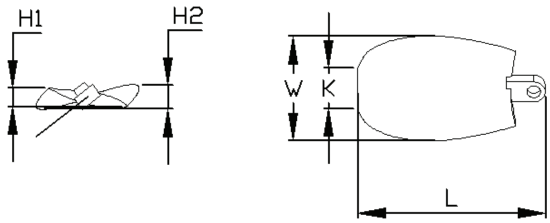

Fig. 16. Specifications of Autonomous Underwater Vehicle propeller blade

Table 6. Work-piece volume, flash volume and under filling volume of Pre-form 1 for various thicknesses when A_{wp}= 626.72mm^2 t_f = 0.5mm

Cases	t_{wp} (mm)	Work-piece volume (mm^3) DEFORM	After removing flash	Under filling volume mm^3	Flash volume (mm^3)
I	2.0	902.88	861.84	254.88	41. 04
II	2.5	1128.60	1077.30	39.42	51.30
III	3.0	1333.80	1116.72	No under filling	217.08

Table 7. Work-piece volume, flash volume, under filling volume and percentage of flash of Pre-form 3 for various thicknesses when A_{wp} = 352.34mm^2 t_f = 0.2mm

Pre-form	t_{wp} (mm)	Work-piece volume (mm^3)	After removing flash	Under filling volume mm^3	Flash volume (mm^3)	Percentage of flash
Pre-form 3	3.0	862.40	823.23	No under filling	39.17	4.54

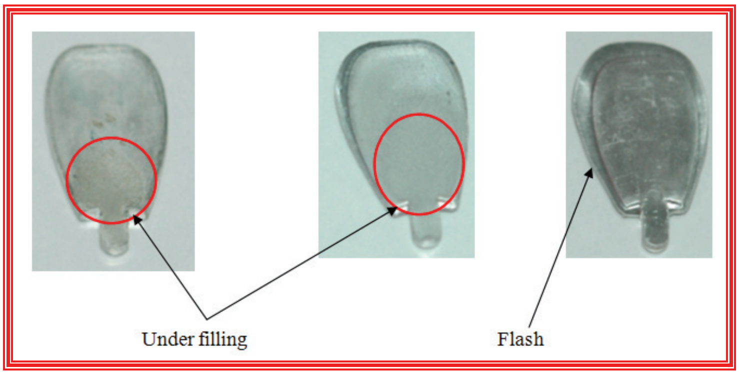

Fig. 17. The experimental forged samples of blade Pre-form1 for cases I, II and III

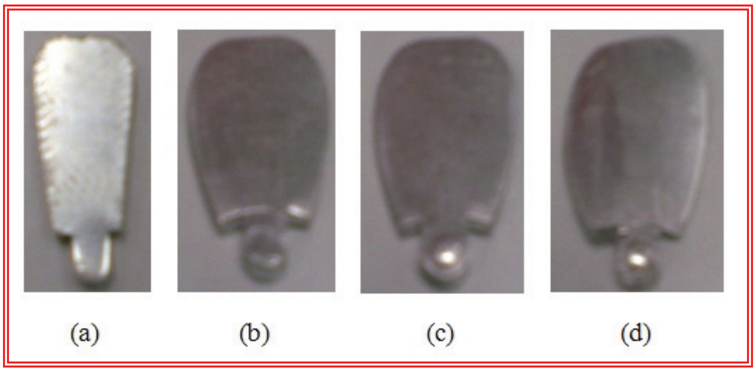

Fig. 18. The experimental forged samples of blade by Pre-form 3 for case III

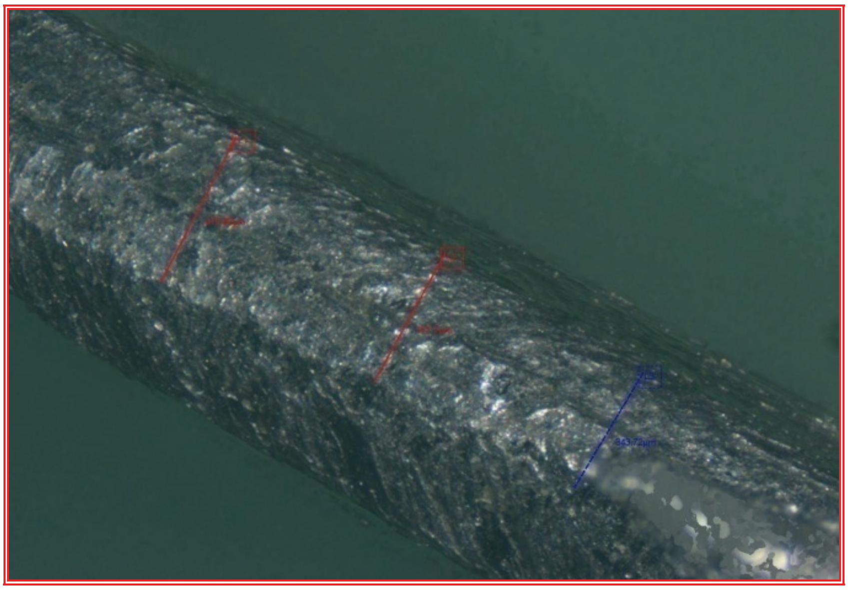

Fig. 19. The experimental forged samples of blade 0.34 mm thickness measured

Fig. 20. The experimental forged samples of Autonomous Underwater Vehicle (AUV) propeller

It is observed that under filling for pre-form thickness is below 3mm, hence keeping thickness 3 mm constant is studied by varying the cross sectional area of the pre-form. After running the experiment for different cross sectional areas of pre-form, the optimum specification for the pre-form is achieved as shown in Fig. 18a. In the second stage of the process, it is observed that there is no under filling and less flash. By optimizing the pre-form, one process could be reduced i.e. trimming of flash, hence the process is optimized. Figure 18d depicts the forged blade with no flash and no under filling; the right side of the blade has 0.34mm thickness as shown in Fig. 4.19. This thickness could not be achieved by using 3mm thickness pre-form 1, but is nearly achieved by using the optimized pre-form. Hence, it is concluded that the pre-form 3 is optimum. Figure 20 depicts the view of assembly of propeller made for Autonomous Underwater Vehicle (AUV).

5. CONCLUSION

The optimum work-piece is found for the flash-less forging and volumetric analysis is carried out. The process is also optimized as it could reduce one stage (the trimming process) by using Pre-form 3; the flash is reduced to 39.17mm^3 and 4.54%. It is observed that as the flash decreases, the load required is also reduced. The minimum thickness of 0.34mm at the front side of the blade is achieved while the required was 0.3mm with hydrodynamic profile. In this case too, the FEM results are compared with the experimental results and found to be good and well-matched. In the present study, the modularized AUV propeller hubs and the blade are produced successfully by cold forging process. Detailed volumetric analysis, work-piece optimization and handling of complex and thin geometries are the remarkable contributions in this work. The stress and thermal analysis to study the die life is the future scope.

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