

Full Length Research Paper

Manufacturing of AA6061 propeller for AUV application using cold forging process

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Accepted 23 December, 2011

Recently, faster and energy saving propeller have become the focus of attention in the marine industry. Furthermore, changeability of the blade is also taken into account for faster replacement and repair works. The objective of the paper is to present the error assessment of the designed Autonomous Underwater Vehicle (AUV) propeller blade. The paper briefly discusses the design steps involved including optimization and fabrication process. The error is assessed based on geometrical and dimensional accuracy of the forged blade utilizing the conventional measurement equipment and finite element analysis. The discussion is focused on the error caused by the manufacturing process. The error was measured based on the thickness and twist angle deviation as compared with the nominal model. The error committed during the assembly in the pin head is also presented.

Key words: AUV, cold-forging, geometrical-defect, material-flow.

INTRODUCTION

The recent demand for underwater vehicles requires smaller and energy-efficient technology. Three major areas that are being intensely highlighted are the selection of suitable material, propeller design, and energy sources (Chyba et al., 2009). Marine propellers are usually made from metal-based material such as manganese–aluminum–bronze and nickel–aluminum–bronze (Motley et al., 2009). Recently, there has been a tendency to choose composite plastic propellers due to their flexibility (Lin et al., 2009). In many ways, the material determines the propellers' suitability when matched with engines of varying horsepower (hp). For example, composite-based propellers are used on engines of less than 50 hp, aluminum propellers are preferred on engines of up to 150 hp, and bronze propellers are used for engines with lower power demand. Composite propellers cannot be repaired and

are difficult to produce in small sizes. Aluminum propellers are more expensive than composite propellers but are better in terms of corrosion resistance (Tang et al., 2006), and fortunately, they meet the required part strength (Mukhopadhyay et al., 2006) for marine application. In addition, aluminum blades can be repaired. The most versatile material is stainless steel; it is extremely durable and allows blades to be as thin as possible to reduce resistance in the water. However, it is quite expensive. Stainless steel propellers are also stronger and allow for modifications or repair work (Ono et al., 1993).

Conventionally, propellers can be manufactured by casting (Ganesh et al., 2008) and machining (Kuo and Dzan, 2002). The disadvantages of a casted propeller are on part strength and surface finish, and it usually requires machining to obtain the desired surface quality. The strength of propellers manufactured by casting is 17% lesser as compared to that of propellers made from long glass fiber-reinforced polyamide thermoplastic (Marsh, 2004). In the cast products, the flaws and thermal problems have to be solved and the grain structure

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cannot be controlled (Kalpajian and Schmid, 2009). Compared to cold forging, the production time of the casting process is significantly higher. In contrast, machining complicated profiles like a propeller is difficult and time consuming. The collision between tool and workpiece, and material wastage and tool vibration is more (Young et al., 2004) compared to that in the forging process. In addition, similar to the casted propeller, the grain structure cannot be controlled through machining. Since the profile of the propeller is considered to be complex, therefore tight manufacturing tolerance need to be carried out in order to avoid component error.

Component errors can be divided into two categories: shape error and dimensional error (Lange, 1985). Shape error is the deviation of the geometrical form of a part, and dimensional error is the deviation of the actual dimension from the desired value. Arentoft and Wenheim (1997) classified forging part defects into six: fold, shear defect, surface defect, form defect, crack, and structural defect. There are many causes of defect, including die deflection, yielding or wear, and eccentricity or buckling due to flow imperfection. Chan et al. (2009) proposed a dynamic change of tooling geometry to control the most common flow-induced defect, that is, folding. Other types of defects such as die filling and barrel formation during the lateral extrusion process have been discussed by Tahir (2007). Sun et al. (2010) studied the material flow behavior of magnesium-alloy in the formation of hook, sidewall and boss during press forging of notebook case. They introduced methods to avoid the material to flow outwards, which causes the geometrical defect. Mohammadi and Sadeghi (2010) found that by optimizing process sequence, surface defect can be prevented. While Qamaz (2010), investigated the effect of shape complexity and dead metal zone (DMZ) to the quality of cold extruded part. In other case, Khaleed et al. (2011) presented a preform optimization in achieving flashless forging. Even though many researchers have presented various issues and proposed different method to prevent the forging defect. The assessment of a complex cold forging geometries such as propeller has not been reported so far.

The purpose of this paper is to present the next stage of design and manufacturing of the AUV propeller by focusing on error assessment of the blade. This is important since the accuracy of the blade is very crucial and may affect the performance of the propeller. The developed process and the assessment method used are very beneficial to the marine industries in improving the quality and reliability of the current propeller design.

MATERIALS AND METHODS

Design requirement

The hydrodynamic design of a propeller blade is optimized to

achieve the required thrust. Theoretically, an airfoil can be characterized by the angle of attack, lift coefficient, and drag coefficient. A propeller, on the other hand, can be presented in terms of advance ratio, thrust coefficient, and power coefficient. Efficiency can be calculated by dividing the thrust by the consumed power and multiplied with the flight velocity. The total radius R of the propeller is the distance from the center to the tip. The chord length c is the straight-line width of the propeller at a given distance along the radius. Depending on the propeller design, the chord length may be constant along the entire radius or it may vary along the radius of the propeller. Another variable is the twist angle β of the propeller, which may also vary along the radius of the propeller (Kerwin, 2001).

Modeling

The design process is a challenge, and it is more challenging to obtain optimum design without defect and wastage. For this purpose, the designer can model the product or the process before production takes place. This can be done by simulating the process involved in the manufacturing and applying all the changes and modifications. Therefore, in this process, CAD/CAE/CAM tools are employed. The design process and fabrication of the propeller will be discussed in detail.

Initially, the propeller profile is obtained based on the programming code named PVL (Abu-Bakar et al., 2009). By setting required design parameters such as thrust and power, the efficiency of the propeller's initial profile can be determined analytically by employing Computational Fluid Dynamic (CFD) (Abu-Bakar et al., 2010). Afterward, the profile is converted to a Computer Aided Design (CAD) model in the available software SolidWork as shown in Figure 1a.

The numerical simulation is more focused on the blade because the shape is more complex. Initially, the simulation is performed in 2D. Based on the CAD model, the blade is divided into several sections. The simulations are run simultaneously, and from the result, the tooling will be designed. Khaleed et al. (2011) successfully simulated a 3D view of the forging process using DEFORM. Table 1 summarized the material properties of the workpiece. Meshing is performed by using hexahedron elements; the number of elements used for work-piece, punch and die are 2000 and 50 500 respectively.

At this stage, numerical simulation is performed to obtain the optimal process. Several parameters are taken into consideration, including the maximum capacity of the press machine, that is, maximum load, complexity of the tooling set, and machine-ability of the punch and insert. From the simulation, the optimal process sequence involves five stages: punching to obtain the preform, shaping, trimming, pin heading, and twisting. For the hub, the process involves two steps: preparation of the billet and end by forming process. Since the process is quite direct and error is not critical, it is not highlighted in the discussion. There are two aims for the optimization stage: minimize the flash and avoid underfills (Khaleed et al., 2011). Flashless forging leads to a reduction in the load required to forge, as well as wastage of material, time, and number of operations for a complex component like an AUV propeller. This is similar for the hub as discussed in Khaleed et al. (2010). Figure 2 shows the overall dimension of the propeller.

Fabrication

The propeller is finally fabricated using 100 tone mechanical press machine and the final assembly of the propeller is as shown in Figure 1b. Table 2 lists the specification of the machine. The

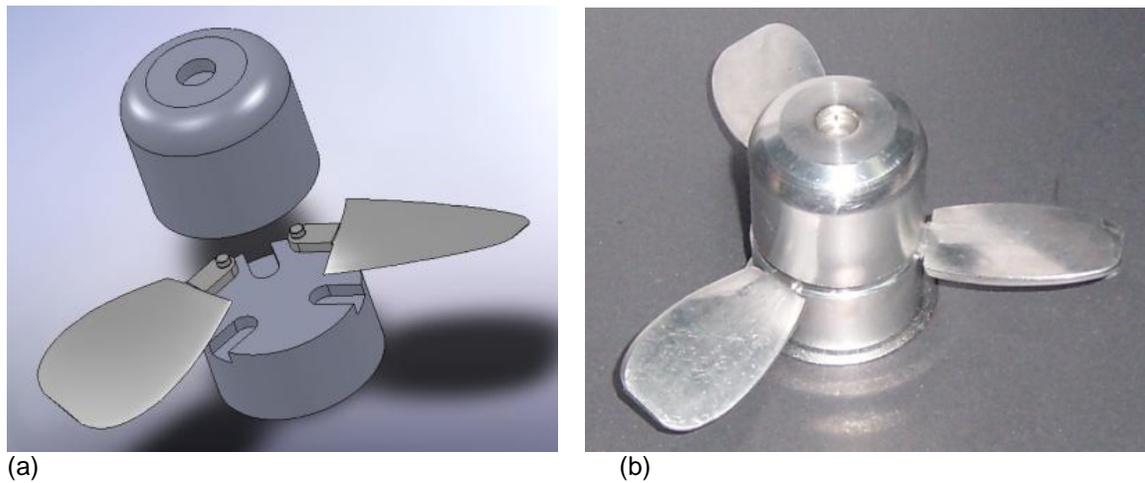


Figure 1. (a) CAD model of the propeller and (b) final assembly of the cold forged propeller.

Table 1. Material properties of the workpiece.

Parameter	Workpiece
Material type	AA 6061
Modulus young (GPa)	70
Poisson ratio	0.35

velocity of the punch is 250 mm/min. To reduce friction, ordinary engine oil was used and the process was conducted at room temperature.

DISCUSSION

Propeller performance mainly depends on the accuracy of the forged blade, and the blade assembly. In the present study, the profile error of the blade is studied by comparing the model of the CAD and the measured dimension using Coordinates Measurement Machine (CMM). Two parameters are measured: part thickness and twist angle. The blade is divided into five sections because the blade has a complex profile. Deviation between the twist angle obtained from CMM and the CAD model is then determined by referring to the definition given by Makem et al. (2008). The results are listed in Table 3. A similar pattern found for the twist angle is summarized in Table 4. The result depicts that as the twist angle increases, the deviation also increases. In the case of thickness, the deviation is considered large, because the measurement is made without taking into consideration the forging gap (0.5 mm in this case). Even though the thickness error and twist angle seem large, but from the experiments conducted by Husaini (2011), it

was found that the propeller efficiency achieved the required efficiency.

The cross-section view of the final assembly of the blade and the role of the pin head is illustrated in Figure 3. To predict the occurrence of defects and the effect to the blade assembly, a simulation of the pin head embossing process is performed using a commercial analytical code for 2D implicit-solution finite element methods, namely, DEFORM-2D. The rigid-plastic finite element model consists of a preform/workpiece, a top die, and bottom die. The workpiece material is set as an elasto-plastic type and both dies are considered as rigid body. The preform is placed between the dies before the embossing takes place.

In this study, two major defects were measured, the unfilled region and bulging. The unfilled region is quantified based on a filling ratio, which is the ratio of the filled region to the fully filled. The maximum load to perform this task is approximately 60 MPa. In the case of the conventional embossing process, the stress distribution shows the concentrated tensile stress around the sliding region. This tensile stresses increase as the punch stroke increased. At a lower stroke, the stress concentration is localized more at the right section and the largest stress is observed near this region. Till the end of the pressing process the localization continues,

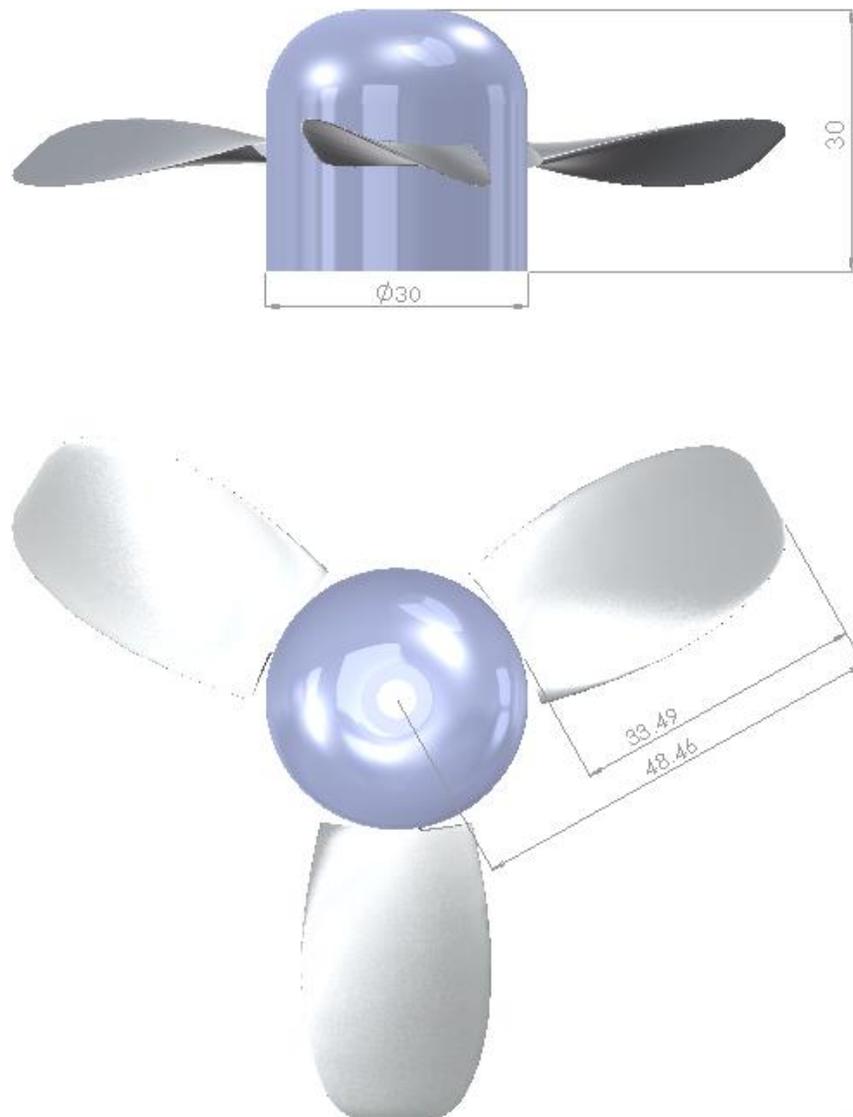


Figure 2. CAD model of the propeller.

Table 2. Machine specifications.

Item	Specification
Type	Single and continuous stroke
Model	J23
Capacity	1000 kN
RPM	1455 rpm
Valve pressure	0.2–1 MPa

resulting in a lesser distribution area.

In this study, the main interest is the flow of the material of the right section. For the punch, which initially is 3 mm

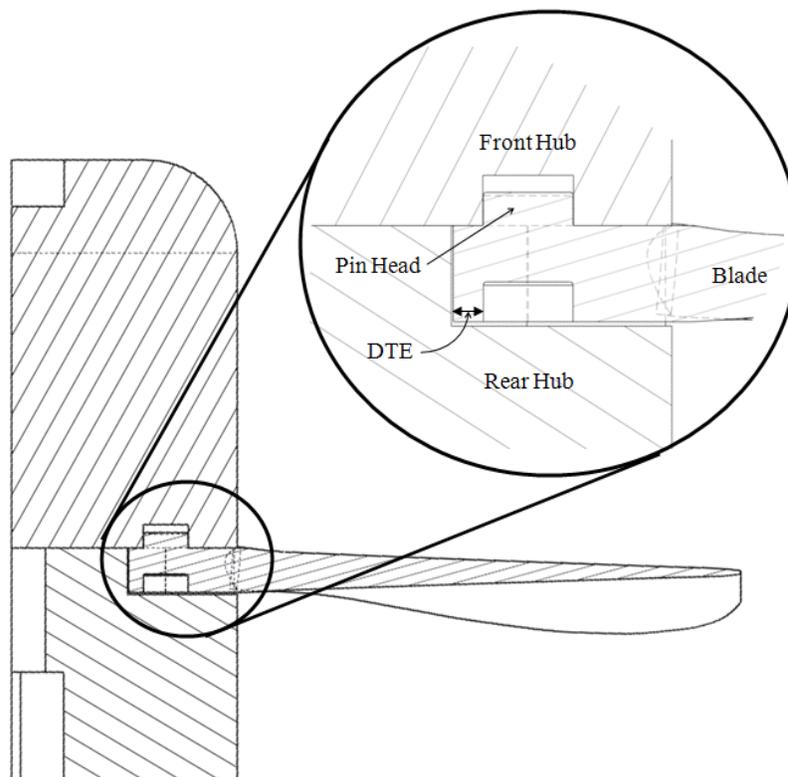
in diameter and 2 mm in depth, as the punch stroke increases, the material follows the punch and the cavity can only be spotted after the stroke reaches 1.0 mm.

Table 3. Average blade thickness deviation.

Section	Measured, mm	CAD Model, mm	% Error
1	3.10	2.78	10.32
2	2.90	2.18	24.83
3	2.35	1.56	33.62
4	1.90	1.01	46.84
5	1.55	0.71	54.19

Table 4. Twist angle deviation.

Alicona	CAD Model	% Error
2.54	3.80	33.16
4.27	6.76	36.83
7.67	13.90	44.82
11.20	20.48	45.31
11.50	22.35	48.54

**Figure 3.** Final assembly of the AUV propeller.

Until the punch stroke reaches 2.0 mm, the material tend to flows outward and, as a result, bulging occurs as illustrated in Figure 4.

In another case, the edge of the right of the workpiece is tilted upward because of the cyclone-type material flow pattern. This phenomenon can only be observed for the

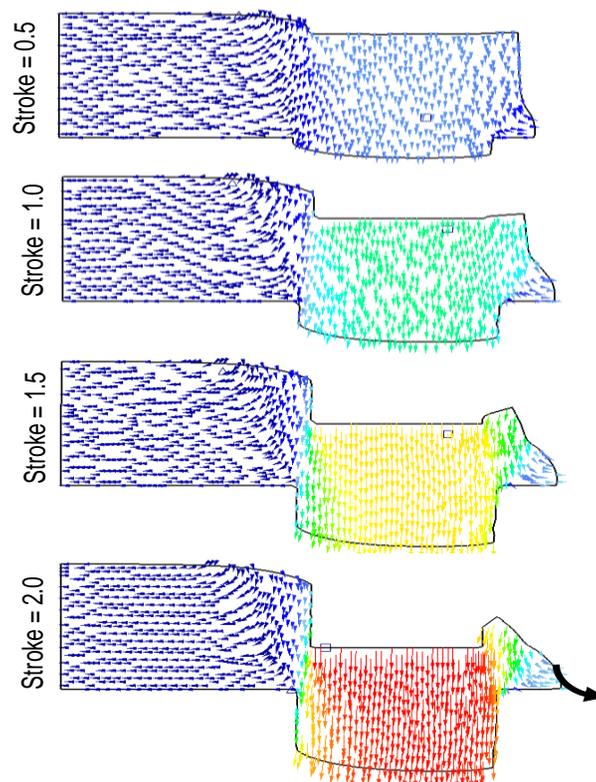


Figure 4. The material flow of the pin head embossing at different punch stroke.

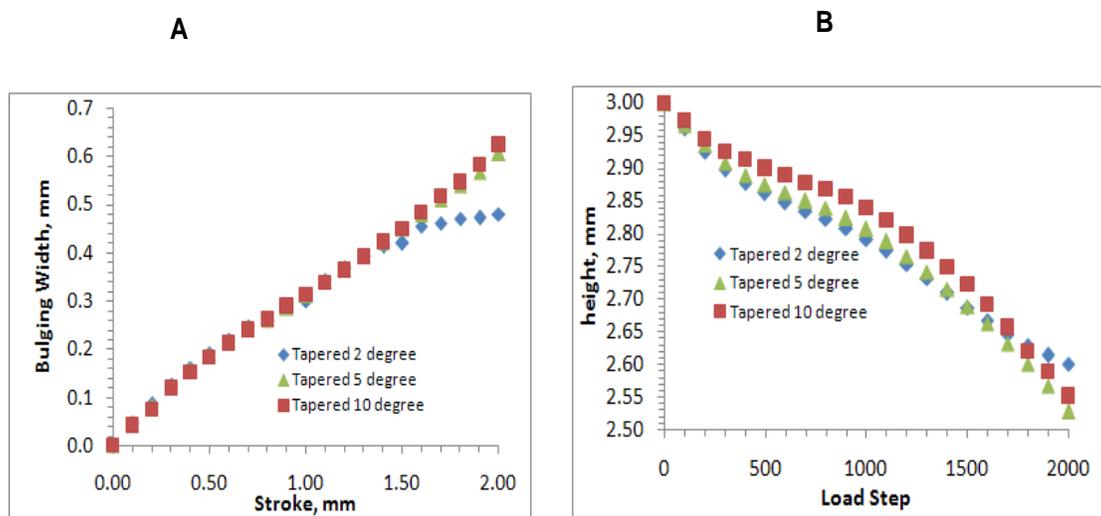


Figure 5. The effect of tapered punch to the (a) height of the right section and (b) bulging width.

tapered punch. Furthermore, the tilting degree increases as the tapered angle increases; this is also one reason for the increment of the bulging width. Two parameters are measured on the embossed pin head, namely, height

of the edge and bulging width. Based on the result, the effect of the tapered punch on the measured features are still less. A similar pattern can be seen for all three angles as shown in Figure 5.

Conclusion

The main objective of this paper is to present the novel manufacturing process of a propeller blade using the cold forging process. The main contribution of this paper is on the accuracy evaluation of the cold forged blade. Two criteria, part accuracy and assembly accuracy, are investigated. Part accuracy is concerned more on the accuracy of the blade features; in this case, thickness and twist angle deviation are measured. For assembly accuracy, the effect of a few design parameters on the accuracy of the cold embossed pin head are studied. The simulation is performed based on material flow pattern. Two types of defects are measured, including unfilled region and bulging. The result depicts that the only parameter that significant to the defect is the distance of the pin to the edge or DTE. Even based on the simulation result, the introduction of the tapered punch still gives minimal effect. It is found that the forged pin head and the simulated one show good agreement geometrically.

ACKNOWLEDGEMENTS

The authors would like to acknowledge the Ministry of Higher Education and Universiti Sains Malaysia for their sponsorship through Fundamental Research Grant Scheme.

REFERENCES

- Abu-Bakar MH, Samad Z, Arshad MR (2009). CFD Simulation of Cooperative AUV Motion, *Indian J. Marine Sci.*, 38(3): 346-351.
- Abu-Bakar MH, Samad Z, Arshad MR (2010). Performance Analysis of AUV Propeller using CFD, 3rd Int. Conf. on Underwater System Technology: Theory and Applications 2010 (USYS'10), Cyberjaya, Malaysia, pp. 204-208.
- Arentoft M, Wanheim T (1997). The basis for a design support system to prevent defects in forging, *J. Mater. Process. Technol.*, 69(1-3): 227-232.
- Chan WL, Fu MW, Lu J, Chan LC (2009). Simulation-enabled study of folding defect formation and avoidance in axisymmetrical flanged components, *J. Mater. Process Technol.*, 209(11): 5077-5086.
- Chyba M, Haberkorn T, Singh SB, Smith RN, Choi SK (2009). Increasing underwater vehicle autonomy by reducing energy consumption, *Ocean Eng.*, 36(1): 62-73.
- Ganesh D, Jain M, Singh PP, Radhakrishnan KK, Bhattacharya B (2008). Pressure casting of composites propellant, *Ind. J. Chem. Technol.*, 15(4): 420-423.
- Husaini MHAB (2011). Design and Analysis of Cold Forged AUV Propeller, MSc Thesis, Universiti Sains Malaysia.
- Kalpajian S, Schmid SR (2009). *Manufacturing Engineering and Technology*, Sixth Edition, Prentice Hall Inc.
- Kerwin JE (2001). *Lecture Notes: Hydrofoils and Propellers*, Massachusetts Institute of Technology.
- Khaleed HMT, Samad Z, Othman AR, Mujeebu MA, Abdullah AB, Ab-Kadir AR, Badruddin IA, Salman Ahmed NJ (2011). Computer-aided FE Simulation for Flash-less Cold Forging of Connecting Rod without Under-filling, *Arabian J. Sci. Eng. B: Eng.*, 36(5): 855-865.
- Khaleed HMT, Samad Z, Othman AR, Mujeebu MA, Abdullah AB, Arshad AR, Ab-Kadir AR, Hussaini A (2010). FEM and experimental analysis of flash-less cold forging of propeller hubs and blade of autonomous underwater vehicle, *Proc. Instn. Mech. Eng. Part B, J. Eng. Manuf.*, 224: 1455-1467.
- Khaleed HMT, Samad Z, Othman AR, Mujeebu, MA, Abdullah AB, Zihad MM (2011). Work-piece optimization and thermal analysis for flash-less cold forging of AUV propeller hubs - FEM simulation and experiment, *J. Manuf. Process*, 13(1): 41-49.
- Kuo HC, Dzan WY (2002). The analysis of NC machining efficiency for marine propellers, *J. Mater. Process Technol.*, 124(3): 389-395.
- Lange K (1985). *Handbook of Metal Forming*, McGraw-Hill, New York.
- Lin CC, Lee YJ, Hung CS (2009). Optimization and experiment of composite marine propellers, *Composite Structures*, 89: 206-215.
- Makem J, Ou H, Armstrong CG, Rennie A, Nikov S (2008). A Virtual Inspection Technique for Assessing the Dimensional Accuracy of Forged Compressor Blades Using FE Modeling and CMM Inspection. *Inter. J. Mater. Form.*, 1: 375-378.
- Marsh G (2004). A new start for marine propellers. *Reinforced Plastics*, 48(11): 34-38.
- Mohammadi MM, Sadeghi MH (2010). Numerical and Experimental Investigation of Forging Process of a CV Joint Outer Race, *Int. J. Res. Rev. App. Sci.*, 2(1): 1-8.
- Motley MR, Liu Z, Young YL (2009). Utilizing fluid-structure interactions to improve energy efficiency of composite marine propellers in spatially varying wake, *Composite Struct.*, 90(3): 304-313.
- Mukhopadhyay SK, Basu J, Chaulia PK (2006). Strength analysis of an aluminum-alloy component of circular geometry developed by cold forming and friction welding method, *J. Sci. Ind. Res.*, 65(3): 227-231.
- Ono S, Saito M, Matsuo S (1993). Microstructure and mechanical properties of 18 mass% chromium cast stainless steel for marine propeller. *J. Jap. Inst. Metallurgy*, 57(7): 761-766.
- Qamar SZ (2010). Shape Complexity, Metal Flow, and Dead Metal Zone in Cold Extrusion, *Mater. Manuf. Process.*, 25: 1454-1461.
- Sun C, Zhang SH, Tang WD, Wang ZT (2010). Press Forging of Magnesium-Alloy Notebook Case with Complex Geometry, *Mater. Manuf. Process.*, 25(7): 534-538.
- Tahir A (2007). A study of barreling profile and effect of aspect ratio on material flow in lateral extrusion of gear-like forms, *Indian J. Eng. Mater. Sci.*, 14(3): 184-192.
- Tang CH, Cheng FT, Man HC. (2006). Laser surface alloying of a marine propeller bronze using aluminum powder: Part II: Corrosion and erosion-corrosion synergism, *Surface Coatings Technol.*, 200(8): 2594-2601.
- Young HT, Chuang, LC, Gerschwiler, K, Kamps S (2004). A five-axis rough machining approach for a centrifugal impeller. *Inter. J. Adv. Manuf. Technol.*, 23: 233-239.